# Woods Hole Oceanographic Institution


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# ABSTRACTS OF PAPERS

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# PREFACE

This volume contains all abstracts submitted for publication during calendar year 1987 by the staff and students of the Woods Hole Oceanographic Institution. Because some of the abstracts may not be published in the journal to which they have been submitted initially, we have purposely omitted identifying the journals. The volume is intended to be informative, but not a bibliography.

The abstracts are listed by title in the Table of Contents and are grouped into one of our five departments, marine policy, or the student category. An author index is presented in the back to facilitate locating specific papers.

Robert B. Gagosian
Associate Director for Research

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# DEPARTMENT OF BIOLOGY

Richard H. Backus, Chairman

## MACROFAUNAL COLONIZATION OF DISTURBED DEEP-SEA ENVIRONMENTS AND THE STRUCTURE OF DEEP-SEA BENTHIC COMMUNITIES

J. Frederick Grassle
and Linda S. Morse-Porteous

Trays of azoic sediment and organic additions were used to determine the responses of deep-sea species to disturbance at two sites south of New England: Deep Ocean Station One (DOS 1) at 1800-m depth and Deep Ocean Station Two (DOS 2) at 3600-m depth. Species diversity was higher in the natural community at the deeper site. Rates of colonization were similar at the two sites, but slow relative to those in similar experiments conducted in shallow water. Trays of azoic sediment resting on the bottom for five years did not achieve the density of individuals or species found in the natural community. Species of polychaete worms in the families Spionidae, Capitellidae, and Sigalionidae were the most consistent colonists regardless of the kind of disturbance. Highest densities were achieved in patches of organic material. At the deeper DOS 2 site, densities of the sibling species of Capitella were 829 per $m^2$ in the vicinity of wood blocks, and the dorvilleid polychaete, Ophryothrocha sp. A, occurred at 1274 per $m^2$ in natural, patchy accumulations of decomposing seaweed, Sargassum. The response to disturbance represented by the sediment trays was much more variable at DOS 2 than at DOS 1, with several taxa achieving high densities in only one tray. Pholoe anoculata, Ophelina cylindricaudata, and Hesionidae spp. were consistent colonists of the sediment trays at DOS 1. A few taxa such as Capitella spp., Myriotrochus spp. and Ophiura ljungmani increased greatly under screens. Predators excluded by the screens in these experiments may normally prevent juveniles of these species from becoming abundant. Occasional escape from predation may explain the rare instances of dense populations of these species. The responses of deep-sea populations to Sargassum, wood and azoic sediments indicate that a temporal mosaic of small-scale patches of organic enrichment and disturbance are very important in structuring deep-sea communities. The high diversity of species in the deep sea is maintained by: (1) patchiness of organic input against a background of low productivity; (2) sporadic, small-scale, discrete disturbance events occurring against a background of relative constancy; (3) the lack of barriers to dispersal among populations distributed over an enormous area.

Published in: Deep Sea Research, 34(12A), 1911-1950, 1987.

Supported by: NSF Grants OCE76-01968, OCE78-19820, OCE81-17586 and OCE83-11201.

WHOI Contribution No. 6407.

## THE STRUCTURE OF DEEP-SEA BENTHIC COMMUNITIES AND MACROFAUNAL COLONIZATION OF DISTURBED DEEP-SEA ENVIRONMENTS

J. Frederick Grassle
and Linda S. Morse-Porteous

Trays of azoic sediment and organic additions have been used to determine the responses of deep-sea species to disturbance at two sites south of New England: Deep Ocean Station One (DOS 1) at 1800-m depth and Deep Ocean Station Two (DOS 2) at 3600-m depth. Species diversity is higher in the natural community at the deeper site but rates of colonization are similar at the two sites. Colonization rates at both sites are slow relative to those in similar experiments conducted in shallow water. Trays of azoic sediment resting on the bottom for five years do not achieve the density of individuals or species found in the natural community. Species of polychaete worms in the families Spionidae, Capitellidae, and Sigalionidae were the most consistent colonists regardless of the kind of disturbance. Highest densities were achieved in patches of organic material. At the deeper DOS 2 site, sibling species of Capitella were 829 per $m^2$ in the vicinity of wood blocks and the dorvilleid polychaete, Ophryothrocha sp. A, occurred 1274 per $m^2$ in natural, patchy accumulations of decomposing seaweed, Sargassum. The response to disturbance represented by the sediment trays was quite variable at DOS 2 with several taxa achieving high densities in only a single tray. Pholoe anoculata, Ophelina cylindricaudata, and Hesionidae spp. were consistent colonists of the sediment trays at DOS 1. Our results provide further support for the hypothesis that a temporal mosaic of small-scale patches of organic enrichment and disturbance are important in structuring deep-sea communities.

Supported by: NSF Grants OCE76-01968, OCE78-19820, OCE81-17586 and OCE83-11201.

WHOI Contribution No. 6407.

## INITIAL EVIDENCE FOR THE TRANSPORT OF BENTHIC INVERTEBRATES ACROSS THE EAST PACIFIC BARRIER

Rudolf S. Scheltema

Since the mid-19th century biologists have considered the east tropical Pacific as a barrier for the dispersal of coastal marine invertebrate species, and more recently it has been maintained that this is so because planktonic larvae are unable to cross such a large expanse of ocean. It seems extraordinary therefore that no observations have been made to determine whether or not larvae of invertebrates are actually transported by the major currents of that region. Plankton samples in the present study show that invertebrate larvae do occur within the east tropical Pacific including, but not restricted to, those of gastropods, polychaetes, sipunculans, decapod crustacea, echinoderms and coelenterates, though as a rule their occurrence there is significantly less than within the central tropical Pacific.

Data from larval distribution suggest that the east tropical Pacific may act as a substantial impediment to many invertebrate forms, but that it is not a complete barrier to dispersal. Accordingly the region is best considered a filter, allowing only species with a potentially long larvae life (i.e., those with teleplanic larvae) while blocking forms that are restricted to a shorter time in the plankton, owing to an inability to delay metamorphosis or that lack any alternate mode of dispersal. The capacity for dispersal by means of planktonic larvae differs among various taxa.

In press: Biological Bulletin.

Supported by: NSF Grant OCE86-14579.

WHOI Contribution No. 6612.

## RECRUITMENT OF MARINE INVERTEBRATES TO HARD SUBSTRATES AT DEEP-SEA HYDROTHERMAL VENTS ON THE EAST PACIFIC RISE AND GALAPAGOS SPREADING CENTER

Cindy Lee Van Dover
and Carl J. Berg, Jr.

Recruitment panels were placed at and near hydrothermal vent communities at three sites on the Galapagos Spreading Center (GSC) and one site on the East Pacific Rise at 21°N. Deployment periods ranged from 26 d (Clam Acres, 21°N) to 260-320 d (Rose Garden, Garden of Eden, Mussel Bed, GSC) to 1216 d (Clam Acres). Recruitment of gastropod post-larvae and juveniles was observed on arrays deployed at Clam Acres for 26 d. Regardless of length of deployment, populations of polychaetes, mollusks, and barnacles colonizing the panels were predominantly postlarval, juvenile, or subadult stages. We suggest that some combination, migration, and predation maintains these populations in immature stages. Size distributions of individuals within a taxon on panels deployed 1216 d are broad, suggesting intermittent or continuous recruitment in many of the vent-associated species rather than a single episodic recruitment event. Folliculinid and foraminiferan protozoans were the most abundant eucaryotic organisms colonizing long-term deployments of arrays at Clam Acres. On the Galapagos Spreading Center, level of recruitment to panels differed among the vent sites, with Rose Garden > Garden of Eden >> Mussel Bed. Recruitment of vent-associated species was greater on panels placed within vent communities compared to panels placed adjacent to these communities. This observation is consistent with the maintenance of vent communities in discrete regions of hydrothermal flux.

Supported by: NSF Grants OCE78-08855, OCE81-17119 and OCE83-11029; NSF Graduate Fellowship and the WHOI Education Office.

WHOI Contribution No. 6684.

## FEEDING BIOLOGY OF THE MID-ATLANTIC RIDGE HYDROTHERMAL VENT SHRIMP: FUNCTIONAL MORPHOLOGY, GUT CONTENT ANALYSES AND STABLE ISOTOPIC COMPOSITIONS

Cindy Lee Van Dover, Brian Fry,
J. Frederick Grassle, Susan Humphris
and Peter A. Rona

A newly described species of shrimp, Rimicaris exoculata Williams and Rona 1986, dominates the megafaunal community at two hydrothermal vent sites on the Mid-Atlantic Ridge. Behavioral observations and gut content analyses indicate that these animals ingest large amounts of sulfide particles from black smoker chimneys. Lipopolysaccharide assays show that gut contents of the shrimp include a large amount of bacterial material, but direct observations of bacteria could not confirm this, probably because of rapid digestion of bacterial cells in the stomach. There is no evidence of chemoautotrophic endosymbionts in this species, based on morphological, stable isotopic, LPS, and RuBCase activity analyses. Instead, we suggest that the shrimp are normal heterotrophs, grazing on bacterial populations associated with the black smoker chimneys. The

ultimate source of carbon for the shrimp is chemosynthetic, as indicated by $\delta\ ^{13}C$ values of -11.6 and -12.1 °/oo in the shrimp tissues. We hypothesize that bacterial populations grazed by shrimp are maintained on chimney surfaces by a combination of rapid bacterial growth rates and continual recharge from a bacterial reservoir that is inaccessible to the shrimp.

In press: Marine Biology.

Supported by: NSF Grant OCE83-11201, NSF Graduate Fellowship, WHOI Education Office and NOAA Vents Program.

WHOI Contribution No. 6444.

## COMPARATIVE ECOLOGY OF HYDROTHERMAL VENT COMMUNITIES ON THE EAST PACIFIC RISE AND GALAPAGOS RIFT

Cindy Lee Van Dover
and Robert R. Hessler

Comparisons of distributions of megafaunal species at hydrothermal vents on the East Pacific Rise and Galapagos Spreading Center can be made at three levels: 1) within a vent field, 2) among vent fields within a cluster on a ridge segment, and 3) among ridge segments. Across forty degress of latitude, megafaunal compositions of vent communities are remarkably consistent at the generic level. Along any given ridge segment, there exists a single species pool from which any vent field draws its fauna. Relative abundances of species within a vent field are determined by a combination of environmental characteristics, biological interactions, and dispersal phenomena.

Supported by: NSF Graduate Fellowship and the WHOI/MIT Joint Program.

WHOI Contribution No. 6654.

## EGG SIZE IN SQUAT LOBSTERS (GALATHEOIDEA); CONSTRAINT AND FREEDOM

Cindy Lee Van Dover
and Austin B. Williams

Within the superfamily Galatheoidea, egg volumes of 52 species in the families Chirostylidae (Chirostylus, Eumunida, Uroptychus) and Galatheidae (Cervimunida, Galathea, Munida, Munidopsis, Pleuronocodes) were determined from measurements of eggs on females in museum collections. Correlations between egg size, body size, brood size, and depth of collection were examined for this data set. In general, significant, positive correlations between egg size and body size and between brood size and body size were observed. We found a strict dichotomy in egg size that corresponds to the generic classification of species examined but not to habitat. We note a narrow range of egg sizes in species presumed to have planktotrophic larvae and a broad range of egg sizes presumed to have lecithotrophic larvae. These observations are discussed in the context of phylogenetic and biological constraints.

Supported by: NSF Graduate Fellowship and WHOI Education Office.

WHOI Contribution No. 6682.

## EFFECT OF Gemma gemma (BIVALVIA) ON Cymenella torquata (POLYCHAETA): TESTING FOR MUTUALISM

James Weinberg

The deposit feeder Clymenella torquata often coexists on sandflats with Gemma gemma, a suspension-feeding bivalve. Previous studies have shown that growth, fecundity and survival of G. gemma are greater because of sediment reworking by the polychaete. If C. torquata benefits from the presence of G. gemma this would represent mutualism, a relatively uncommon interspecific interaction. This was tested in the laboratory by raising C. torquata for 83d at 3 clam densities and at 2 levels of organic mineral aggregates (OMA) added to the sediment surface. OMA concentration was varied to determine whether the positive effect of clams would increase when food within the sediment was scarce. If clams were to have an effect, it was expected to involve ingestion by C. torquata of microbes growing on clam fecal pellets, which are cylindrical and <.25 mm in length. There were significant differences between treatments in percent growth of C. torquata, with increases caused by OMA addition. Clams had no effect on C. torquata growth and there was no significant interaction between OMA and clam abundance on worm growth. Although the mutualism hypothesis was not supported, the results demonstrate that OMA at the surface is a significant food source for C. torquata. This material is probably obtained by the surface-feeding behavior "hoeing". The relationship of food conditions at the surface to surface and subsurface-feeding by C. torquata is discussed.

Supported by: WHOI and the University of Connecticut Doctoral Dissertation Fellowships.

WHOI Contribution No. 6655.

## B I O G E O G R A P H Y  A N D

## S Y S T E M A T I C S

### A NEW SPECIES OF ISOPOD CRUSTACEAN FROM PACIFIC PANAMA, Excirolana chamensis n.sp. (ISOPODA: FLABELLIFERA: CIROLANIDAE)

Richard C. Brusca and James R. Weinberg

A new species of cirolanid isopod is described, Excirolana chamensis n.sp., with remarks on its distribution and ecology. E. chamensis is currently known only from the littoral of Pacific Panama. This brings the number of nominate Excirolana species in the eastern Pacific to ten. Excirolana chamensis is sympatric with the widespread E. braziliensis, and several additional undescribed species in this genus. E. chamensis is a small species (length 2.4–4.3 mm), that can be quickly distinguished from the similar E. braziliensis by its 2-articulate mandibular palp and large stellate chromatophores, as well as other characters noted below.

In press: Los Angeles County Museum of Natural History: Contributions in Science.

Supported by: NSF Grant BSR85-14093 and Postdoctoral Fellowship from the Smithsonian Institution.

WHOI Contribution No. 6422.

### OCEAN CURRENT VARIABILITY AND THE SPAWNING SEASON OF HAWAIIAN REEF FISHES

Phillip S. Lobel

The spawning patterns of four Hawaiian reef fishes with similar reproductive habits, but different biogeographic distributions were studied from September 1980 to October 1981. Two species are Hawaiian endemics [Centropyge potteri (Pomacanthidae) and Chaetodon multicinctus (Chaetodontidae)] and the other two have pan-tropical Pacific distributions [Ctenochaetus strigosus and Zebrasoma flavescens (Acanthuridae)]. These fishes all showed increased spawning activity from January to July. This pattern is prevalent among a majority of coastal marine fishes in Hawaii.

Environmental correlatives to the period of peak reproduction include cycles of A) daylight length and temperature cycles which probably function as proximate cues, and B) seasonal variations in ocean current patterns which may ultimately affect larval survival and dispersal. Peak reproduction takes place during months when 1) mesoscale eddies most likely occur, and 2) the probability is greatest of drifting objects remaining near the islands.

In press: Environmental Biology of Fish.

Supported by: NSF Grants OCE80-09554 and OCE81-17891; DOE Contract DE-A503-83-CE89302; U.S. Army Contract DACA83-C0049; NOAA, Office of Sea Grant, Grant NA86-AA-D-SG090.

WHOI Contribution No. 6633.

### PLANKTONIC CILIATES WITH CHLOROPLASTS: TAXONOMIC DESCRIPTIONS OF ONE NEW SPECIES AND REDESCRIPTIONS OF FOUR SPECIES IN THE FAMILY STROMBIDIIDAE (CILIOPHORA, OLIGOTRICHIDA)

David J. S. Montagnes, Denis H. Lynn, Diane K. Stoecker and Eugene B. Small

Five ciliate species collected from the Woods Hole area were examined by protargol silver staining and SEM. These ciliates have been shown to sequester and use chloroplasts obtained from flagellate prey. One new species, Strombidium chlorophilum n. sp., is described. Four other species, Strombidium capitatum, Strombidium conicum, Strombidium compressum, and Laboea strobila, are redescribed. Characters used in describing the Strombidiidae include cell size and shape, anterior and ventral polykinetids, macronuclear shape and size, the kinetid "girdle", the ventral kinety, the trichites, and the paroral kinety. The rationale of using these characters as taxonomic criteria is discussed.

In press: Journal of Protozoology.

Supported by: NSF Grant OCE86-00765 and NSERC Canada Operating Grant A6544.

WHOI Contribution No. 6547.

## ANCESTORS AND DESCENDENTS: RELATIONSHIPS OF THE APLACOPHORA AND POLYPLACOPHORA

Amelia H. Scheltema

Four organ systems, pericardium of primitive mollusks, shell ontogeny and spicule formation in chitons and aplacophorans, chaetoderm oral shield, and the aplacophoran radula, are described and their relationships discussed. The discussion suggests: (1) a coelomate ancestor of the mollusks; (2) a polyphyletic origin of shell, one for Conchifera and another for chitons; (3) a single class Aplacophora containing two taxa, the Chaetodermomorpha and Neomeniomorpha; (4) an archimolluscan radula with a pair of separate radular membranes bearing rows of single teeth. Evidence is presented which contradicts the following hypotheses: (1) an acoelomate origin of mollusks; (2) the division of aplacophorans into two classes; (3) the derivation of the univalved molluscan shell from a common stem with the eight-shelled chitons. The concept of a subphylum Aculifera is rejected as unnecessary since it holds no essential information.

In press: American Malacological Bulletin.

Supported by: Written without support.

WHOI Contribution No. 6599.

# E C O S Y S T E M S  S T U D I E S

## Salt Marsh Systems

### FACTORS CONTROLLING EMISSION OF DIMETHYLSULFIDE FROM SALT MARSHES

John W.H. Dacey, Gary M. King and Stuart G. Wakeham

The emission of biogenic sulfur gases constitutes about half the atmospheric budget for gaseous sulfur (1). Since dimethylsulfide (DMS) was first implicated as a major component of this flux (2-4), considerable attention has focussed on its emission from various ecosystems. Salt marshes have been identified as one system with high area-specific sulfur emission (5-12). Dimethylsulfide and hydrogen sulfide ($H_2S$) constitute the bulk of the flux from salt marshes, with DMS predominating in vegetated areas of the marsh (5,6,8,10-12). Since $H_2S$ is a product of anaerobic decomposition in sediments, it has been assumed that other sulfur gases emitted from salt marshes also originate from decomposition in sediment. Our research suggests an alternative explanation for DMS fluxes. We have investigated the distribution of DMS and dimethylsulphoniopropionate (DMSP) in salt marshes, and conclude that DMS arises primarily from physiological processes in the leaves of higher plants, mainly one species of grass, Spartina alterniflora.

Furthermore, the emission of DMS from this grass may be influenced by the technique used to measure emission, and emission from sites dominated by S. alterniflora cannot be considered to be representative of marsh flora.

Published in: Nature, 330, 643-645, 1987.

Supported by: NASA Grant NAGW-606.

WHOI Contribution No. 6456.

# G E O C H E M I S T R Y

### HYDROXIDE DECOMPOSITION OF DMSP TO FORM DMS

John W.H. Dacey and Neil V. Blough

The kinetics of DMS production resulting from reaction of $OH^-$ with DMSP were investigated as a function of hydroxide concentrations and temperature. The reaction was first-order with respect to DMSP and $OH^-$. The second order rate constant at 20+/-1°C is 0.0044 $M^{-1}$ $sec^{-1}$. The activation energy for this reaction is 14.4 kcal $mole^{-1}$. Our investigation indicates that the rates of reaction of DMSP with $OH^-$ are very slow at the pH of seawater (about 8 years halflife at 10°C), suggesting that DMSP, which may be a major precursor of DMS in seawater, decomposes in the ocean by other mechanisms. We have found bacteria grown in DMSP enrichment culture produce DMS from DMSP quantitatively at rates many orders of magnitude higher than suggested by the chemical kinetics, suggesting that enzymatic processes may accelerate the production of DMS from DMSP in seawater.

Published in: Geophysical Research Letters, 14(12), 1246-1249, 1987.

Supported by: NASA Grant NAGW-606 and a Mellon Study Award.

WHOI Contribution No. 6566.

## SURFACTANT EFFECTS ON AIR-SEA GAS EXCHANGE UNDER TURBULENT CONDITIONS

Joel C. Goldman, Mark R. Dennett and Nelson M. Frew

In a series of laboratory gas exchange studies we found that a wide assortment of synthetic and natural surfactants in both distilled water and seawater led to reductions in oxygen evasion at the air-liquid interface under high near-surface turbulence that was mechanically-induced. Reductions in gas exchange for all surfactants asymptotically reached a lower limit of ~50% compared to that of a distilled water control. We suspect that surfactants act to reduce gas exchange by creating surface pressure forces that oppose and reduce turbulent eddy velocities and, concomitantly, reduce surface renewal. Reductions in oxygen evasion were not a function of initial surface pressure but maximum reductions occurred at surface pressures $\leq$ 0.5 milliNewtons/ meter. Soluble surfactants, which are known to be very effective in reducing gas exchange and which do not display concentration-dependent surface pressures, may have been present in some of our samples. Results from both an opportunistic sampling survey of marine waters and a cruise to the Sargasso Sea revealed that a gradient in gas exchange reductions from 5-15% in oceanic waters to 50% in nearshore waters exists. However, reductions of 50% were found for surface film material obtained from the Sargasso Sea. Our results, while only indicating the potential for reduction of gas exchange at high turbulence in marine waters, provide some measure of the importance of surface-active materials of biogenic origin in affecting the rate of gas exchange in the oceans.

Supported by: NSF Grant OCE84-09169 and ONR Contract N00014-87-K-0007.

WHOI Contribution No. 6462.

## BIOGEOCHEMICAL CYCLING OF DIMETHYLSULFIDE IN MARINE ENVIRONMENTS

Stuart G. Wakeham and John W.H. Dacey

Dimethysulfide (DMS) plays an important role in the global atmospheric sulfur cycle. This single compound is responsible for a major portion of the reduced biogenic sulfur transferred from marine environments to the atmosphere. For this reason, there is considerable interest in characterizing the biogeochemical processes by which DMS is produced and consumed. Numerous ongoing research projects are presently addressing aspects of DMS cycling in oceanic, coastal, and intertidal environments. This paper presents an overview of the biogeochemistry of DMS in marine systems and synthesizes the current state of knowledge in this area of research.

Supported by: NSF Grant OCE84-16203 and NASA Grant NAGW-606.

WHOI Contribution No. 6702.

# M A R I N E  M A M M A L S

## THE 20-HZ SIGNALS OF FINBACK WHALES (Balaenoptera physalus)

William A. Watkins, Peter Tyack, Karen E. Moore and James E. Bird

Repeated 20-Hz pulse sequences, later identified with finback (Balaenoptera physalus), were prominent in the early records of underwater geophysical and military listening installations (mostly in unpublished or military reports, as in Jensvold and Wright, 1959). These sounds in Bermuda waters were described by Patterson and Hamilton (1964, p. 125) as strong, "pure tone pulsed signals at about 20 cps which repeat at regular intervals several times per minute ... The characteristics of the signals were always the same: a pulse of approximately 20 cps of about 1 sec duration..." The signals sometimes continued for hours, and were reported from both deep and shallow water. Tracks of sources of the sounds were derived from multiple hydrophone records, as on Nantucket Shoals (Walker, 1963, 1964). These sounds had been noted as early as 1950 by researchers of the Woods Hole Oceanographic Institution during deep hydrophone ambient noise recordings at various oceanic locations, but up to that point the signals had not been found in recordings within 500 m of the surface (Watkins, 1981). All these early assessments emphasized the regular characteristics of the signals, which often seemed too mechanically exact to be produced by biological sources.

Published in: Journal of the Acoustical Society of America, 82, 1901-1012, 1987.

Supported by: ONR Contract N00014-85-C-0713.

WHOI Contribution No. 6496.

## PHOTOSYNTHETIC RESPONSE OF *Gonyaulax tamarensis* DURING GROWTH IN A NATURAL BLOOM AND IN BATCH CULTURE

Patricia M. Glibert, Todd M. Kana and Donald M. Anderson

We investigated the photosynthetic behavior of the dinoflagellate *Gonyaulax tamarensis* at various stages during growth in a natural bloom in Salt Pond, Massachusetts, and in laboratory cultures. Photosynthetic capacity ($P_{max(cell)}$), determined using a single-cell isolation technique, increased from 0.25 to 0.32 ng C $cell^{-1}$ $h^{-1}$ during bloom development, then dropped sharply to 0.19 ng C $cell^{-1}$ $h^{-1}$ a few days prior to bloom decline. For *G. tamarensis* cultures grown to nitrogen depletion, both $P_{max(cell)}$ and (cell) decreased several-fold as soon as $NO_3^-$ in the media fell to zero. Several lines of evidence are presented that suggest that nitrogen limitation played an important role in the decline of the *G. tamarensis* bloom, despite the fact that ambient nitrogenous nutrient concentrations did not become depleted in the pond.

In press: Marine Ecology Progress Series.

Supported by: NOAA, Office of Sea Grant, Grants NA84-D-00033 (R/B-59), NA84-D-00033 (R/B-56) and NA86-D-SG090 (R/B-76).

WHOI Contribution No. 6586.

## QUANTITATIVE EVALUATION OF BRINE-LIQUID DISPOSAL IN THE OCEAN

Phillip S. Lobel

Ocean disposal of a concentrated brine-liquid is being considered for a site offshore of Johnston Atoll by the U.S. Army. The brine is a waste by-product of the JACADS project on Johnston Island. Ocean disposal is one of several disposal options under evaluation. This paper outlines methods and procedures for controlled ocean dumping of the liquid brine. The potential biological hazard from these operations was determined to be due to brine concentration; toxic or poisonous materials are not components in the brine. Brine concentration can be carefully controlled and monitored during ocean dumping using advanced oceanographic instrumentation. These control tactics would effectively insure environmentally benign operations.

In press: Proceedings of the Conference on Pacific Basin Management of the 200 Nautical Mile Exclusive Economic Zone (Honolulu, HI, July 1987).

Supported by: U.S. Army Corps of Engineers Contract DACA 83-R-0049 and -0051; NOAA, Office of Sea Grant, Grant NA86-AA-D-SG090; Undersea Research Program, NOAA Grant NA80-AA-8-00075; NSF Grants OCE80-09554 and OCE81-17891.

WHOI Contribution No. 6601.

## IMPACTS OF EXPLORATORY DRILLING FOR OIL AND GAS ON THE BENTHIC ENVIRONMENT OF GEORGES BANK

Jerry M. Neff, Nancy J. Maciolek, J. Frederick Grassle and Michael J. Bothner

The Georges Bank is a large plateau lying within the territorial waters of both the U.S. and Canada, 80 to 325 km east of the Massachusetts coast. It is one of the most productive commerical fishery areas in the world. Many species of finfish and shellfish, including cod, haddock, flounder, ocean scallops and lobster, with a market value in excess of 165 million dollars, are harvested from Georges Bank each year (McLeod and Prescott, 1982).

In addition, the geologic structures underlying the Bank are of the type that may contain substantial reservoirs of petroleum and/or gas. As a result, the U.S. and Canadian oil industries have for several years been interested in exploring for oil and gas on Georges Bank. Exploratory drilling in Lease Area 42 in the south-central portion of the U.S. sector of the Bank began on July 22, 1981, and the last of eight exploratory wells was completed there on September 27, 1982. All eight wells were reported to be dry. It is possible that additional exploratory wells will be drilled in the U.S. and/or Canadian sectors of Georges Bank in the future.

The major environmental concern arising from oil and gas exploration on Georges Bank is that intentional discharges of materials (mainly drilling muds and drill cuttings) from oil rigs during normal exploratory activities might damage the Georges Bank environment, particularly the animals living on or in the bottom sediments upon which commercial species depend for food. Because drilling muds and cuttings are composed primarily of insoluble solids that settle rapidly to the bottom, it is widely accepted that impacts of drilling discharges, if any occur, will be most

severe in the benthos where drilling mud and cuttings accumulate (National Research Council, 1983). If commercial quantities of oil or gas are found, the major concern during the development and production phases of the Georges Bank field would be that accidental spills of crude oil and operational discharges of petroleum hydrocarbon-laden produced water would harm the biota, particularly the floating and pelagic eggs and larvae of commercial fisheries species.

The Georges Bank Monitoring Program was designed by a federal multi-agency panel to address concerns related to the initial exploratory phase of Georges Bank development. The program was funded by the U.S. Department of the Interior, Minerals Management Service (MMS). The major objectives of the monitoring program were to determine where and in what quantities materials discharged to the ocean during normal exploratory drilling operations accumulate, and if these discharges have effects on the benthic infaunal communities of Georges Bank. Results of the three major portions of this program have been described in detail in three separate reports to the Minerals Management Service. These are: benthic ecology (Maciolek-Blake et al., 1985); metals in sediments (Bothner et al., 1985); and hydrocarbons in sediments and biota (Payne et al., 1985).

Supported by: Minerals Management Service Contract 14-12-0001-29192 to Battelle Ocean Sciences (formerly New England Marine Research Labs).

WHOI Contribution No. 6585.

## M I C R O B I O L O G Y

### MICROBIAL MATS AT DEEP SEA HYDROTHERMAL VENTS: NEW OBSERVATIONS

Shimshon Belkin and Holger W. Jannasch

Two recent advances in studies on deep sea hydrothermal vent microbiology are reported: (1) the occurrence of massive Beggiatoa mats at the Guaymas Basin vent site (depth 2003 m) and physiological evidence of their chemoautotrophic activity, and (2) the successful isolation of various extremely thermophilic, fermentative archaebacteria from the 11°N and 21°N East Pacific Rise vents as well as from the Guaymas Basin site. The newly isolated organisms have optimal and maximal growth rates of 86-92°C and 92-98°C respectively.

In press: Symposium on Marine Microbial Mats (Eilat, September 1987), American Society of Microbiology Publishers (Washington).

Supported by: NSF Grants OCE87-00581 and ONR Contract N00014-86-K-0481.

WHOI Contribution No. 6611.

### THE ROLE OF ENDOSYMBIOTIC BACTERIA IN THE NUTRITION OF Solemya velum: EVIDENCE FROM A STABLE ISOTOPE ANALYSIS OF ENDOSYMBIONTS AND HOST

Noellette Conway, Judith McDowell Capuzzo and Brian Fry

C, N, and S stable isotope compositions were investigated in tissues of the protobranch bivalve Solemya velum. This species is known to harbor enodsymbiotic chemoautotrophic bacteria. C and N isotope values were also examined in an enriched bacterial fraction, separated from intact gills by differential centrifugation.

The bacterial fraction and host tissues had similar $\delta^{13}C$ values (-30.9‰ to -33.9‰), suggesting that the endosymbiotic bacteria provide as much as 98% of the carbon requirements of Solemya velum. $\delta^{15}N$ values of both S. velum and the endosymbionts were comparable (4.4‰ to -9.8‰), and considerably lower than those of bivalve controls that do not harbor endosymbionts (Mya arenaria and Tellina agilis, $\delta^{15}N$ = 6.3‰, to 8.5‰). Uptake of pore water ammonium by the endosymbionts and subsequent translocation of nitrogenous compounds to the host, may account for the low $\delta^{15}N$ of S. velum. In this context, the symbionts may provide 100% of the host nitrogen. $\delta^{34}S$ values of S. velum (-26.7‰ to -31.15‰) suggest the use of biogenically produced $H_2S$ as a S source. Both the sulfur and nitrogen stable isotope ratios are among the lowest reported for animal tissues.

This study represents the first attempt to estimate the nutritional significance of bacterial endosymbionts by analyzing the stable isotope ratios of both bacteria and host tissue.

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WHOI Contribution No. 6680.

## THE CONTRASTING EFFECT OF SULFIDE AND THIOSULFATE ON THE SYMBIOTIC $CO_2$-ASSIMILATION IN *Phallodrilus leukodermatus*

O. Giere, Carl O. Wirsen, C. Schmidt and Holger W. Jannasch

Carbon dioxide uptake rates by the symbiotic sulfur bacteria in the gutless marine oligochaete *Phallodrilus leukodermatus* (Annelida) were stimulated by $S_2O_3^=$ and suppressed by $S^=$. Animals which host bacteria containing reserve energy substances, maintained a high short term $CO_2$ uptake activity, while bacteria in worm homogenates and in worms treated with an antibiotic (Baypen) did not show any significant metabolic activity. Absolute uptake rates in *P. leukodermatus* were usually found to be considerably higher than those reported for other animals harboring prokaryotic sulfur-oxidizing symbionts. Utilization of thiosulfate rather than sulfide corresponds with the distribution pattern of the worms and is confirmed in other "thiobiotic" animals. Sulfur stored in the symbiotic bacteria appears to be oxidized to sulfate and excreted when the worms are held under energy-limited conditions. The data emphasize the complexity of the possible metabolic pathways involved in the oxidation of reduced sulfur compounds by bacterial symbionts in marine invertebrates.

In press: Marine Biology.

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WHOI Contribution No. 6502.

## CHEMOSYNTHETICALLY SUSTAINED ECOSYSTEMS IN THE DEEP SEA

Holger W. Jannasch

In press: Chapter in the book "Biology of Autotrophic Bacteria", H.G. Schlegel and B. Bowien (editors), Science Technical Publishers, Madison.

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WHOI Contribution No. 6642.

## ISOLATION OF EXTREMELY THERMOPHILIC, FERMENTATIVE ARCHAEBACTERIA FROM DEEP SEA GEOTHERMAL SEDIMENTS

Holger W. Jannasch

Geothermally heated sediments were collected at a tectonically active vent site (Guaymas Basin, Gulf of California; depth 2000 m) for an extensive search for extremely thermophilic microorganisms of potential biotechnological importance. Enrichment and isolation procedures were based on the results of prior studies on the inorganic and organic chemical composition of the sediments as well as temperature profiles of the cores collected. Preliminary physiological and systematic data on the first group of isolates obtained show characteristic differences to the hitherto known extremely archaebacteria.

In press: Biotechnology Applied to Fossil Fuels, D.L. Wise (ed.), CRC Press.

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WHOI Contribution No. 3687.

## LEBEN IN DER TIEFSEE: NEUE FORSCHUNGSERGEBNISSE

Holger W. Jannasch

A report on recent progress in deep sea microbiology emphasizing adaptations to in situ pressures and temperatures as well as the chemosynthetic support of hydrothermal vent communities.

In press: Naturwiss. Rundschau.

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WHOI Contribution No. 6526.

## *Thermotoga neapolitana* sp. nov. OF THE EXTREMELY THERMOPHILIC, EUBACTERIAL GENUS *Thermotoga*

Holger W. Jannasch, Robert Huber, Shimshon Belkin and Karl O. Stetter

The genus *Thermotoga* comprises the only extreme thermophiles among the eubacteria growing at temperatures up to 90°C. Phylogenetically they represent the closest relative to the archaebacteria. Strain NS-E was obtained from a shallow water marine hydrothermal vent at Lucrino near Naples and named *Thermotoga neapolitana*.

In press: Archives of Mircobiology.

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WHOI Contribution No. 6444.

## A MICROBIOLOGICAL STUDY OF GUAYMAS BASIN HIGH TEMPERATURE HYDROTHERMAL VENTS

David M. Karl, Gordon T. Taylor, James A. Novitsky, Holger W. Jannasch, Carl O. Wirsen, Norman R. Pace, David J. Lane, Gary J. Olson and Stephen J. Giovannoni

Water samples and suspended particulate matter were collected from three high temperature (156-319°C) hydrothermal vents in the Guaymas Basin during July 1985, and were analyzed for major nutrients and for the presence of viable or metabolically active microorganisms. From some samples of hot vent waters, measured in situ at >150°C, extremely thermophilic bacteria could be enriched at 80°C. The isolates showed optimal growth rates at 88°-90°C, did not grow at 93°C and did not survive at 110°C. Traces of ATP (<10 ng $l^{-1}$) were found in the same samples, and a low level of $^{3}$H-adenine and $^{14}$C-glutamate incorporation could be measured, but with maximum rates at 45°C. These results argue against a high temperature origin of the organisms. Two experimental devices were deployed in situ, one of them aiming at a colonization of cells, if present, within a chamber place over a hot vent plume ("vent cap") and the other one aiming at an entrapment of cells, if present, within a fiberglass mesh placed deeply within the throat of a hot vent ("smoker poker"). Neither experiment resulted in conclusive evidence for the existence of bacterial cells, viable or not, in the hydrothermal fluid of the black smokers examined. Growth tests of the sporadic thermophilic isolates at 180°C and 260 atm of pressure were negative. We conclude that the variability of conduit formation affecting the changing flow and temperature of individual black smokers result in periodic or continuous entrainment of bacterial cells (contaminants) from the dense populations of the surrounding waters and external surfaces of smoker chimneys.

In press: Deep Sea Research.

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WHOI Contribution No. 6544.

## THE CYTOCHROMES OF A MARINE *Beggiatoa*

Roger C. Prince, Karen E. Stokley, Copper E. Haith and Holger W. Jannasch

Naturally grown *Beggiatoa* filaments, occurring in massive near-monocultures at a "black smoker" wall of the Guaymas Basin hydrothermal vent site, were harvested and used for the analysis of their cytochromes. The cytochromes have been characterized by gel permeation chromatography, optical spectroscopy and redox potentiometry. Only *c*-type cytochromes were detected; a small, high potential cytochrome *c* that seems typical of its class, and a large complex ($M_r$ 210,000) containing at least four thermodynamically distinct *c*-type hemes, which was partially dissociated by chromatography on DEAESepharose. The hemes of the large complex have appropriate oxidation-reduction midpoint potentials ($E_{m7}$ + 240 mV, +15 mV, -160 mV, -340 mV) to be involved in the metabolism of sulfide, which is presumed to be the source of reductant for this organism.

In press: Archives of Microbiology.

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WHOI Contribution No. 6618.

## FRACTIONATION OF STABLE CARBON ISOTOPES DURING CHEMOAUTOTROPHIC GROWTH OF SULFUR-OXIDIZING BACTERIA

Edward G. Ruby, Holger W. Jannasch and Werner G. Deuser

Laboratory-grown strains of chemoautotrophic *Thiomicrospira* sp. strain L-12 and *Thiobacillus neapolitanus* produced cell carbon that was 24.6 to 25.1 ppt (24.6 to 25.1 mg/g) lower in $^{13}$C isotope abundance than the ambient source of carbon dioxide and bicarbonate. This degree of $^{13}$C isotope depletion was comparable to that found in organic material produced in deep-sea hydrothermal-vent communities.

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WHOI Contribution No. 6405.

## THE EFFECT OF FIXATION ON PARTICLE RETENTION BY MICROFLAGELLATES: UNDERESTIMATION OF GRAZING RATES

M.E. Sieracki, L.W. Haas, David A. Caron and E.J. Lessard

The uptake of fluorescent particles by

protists and filter-feeding metazoa is being used increasingly by microbial ecologists to study feeding behavior and measure grazing rates. Recent studies of microflagellate uptake of these inert particles have yielded inconsistent results. In particular, grazing rates determined from fluorescent particle uptake are often less than rates measured using other techniques. These low uptake rates have been attributed to osmotrophy, food quality or size selection, rapid egestion of inert particles, and the slower feeding by free-living, as opposed to attached, protists. We have found that a variety of flagellates egest food vacuole contents upon fixation with several commonly used agents including glutaraldehyde and formaldehyde. During time course experiments, the observed microsphere uptake rate for a small chrysomonad flagellate using 1% glutaraldehyde was only 6% of the rate obtained by using the fixation method of van der Veer (1982) (2% acrolein, 2% glutaraldehyde and 1% tannic acid), modified for epifluorescence microscopy. Uptake rates of several mixed flagellate populations also were 2.4 to 3.1 times higher using the modified van der Veer method than with 1% glutaraldehyde. The average number of ingested microspheres $cell^{-1}$ using this method was similar to that observed in live cells immobilized with $NiSO_4$. Glutaraldehyde also caused the egestion of Synechococcus sp. cells and fluorescently labelled bacteria from the chrysomonad flagellate. We conclude that previous studies using common aldehyde fixation with particle uptake for measuring rates of microflagellate bacterivory have significantly underestimated actual rates of consumption, and that these studies must be re-evaluated, and perhaps repeated, using effective fixation methods.

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WHOI Contribution No. 6487.

## ISOLATION AND GROWTH OF MARINE PLANKTONIC CYANOBACTERIA

John B. Waterbury and Joanne M. Willey

Cyanobacteria are widespread in marine habitats, especially in the warmer temperate and tropical regions, where they are important both as primary producers and nitrogen fixers. The overall taxonomic diversity of marine forms is comparable to that found in freshwater and terrestrial habitats. However, particular marine habitats (e.g., the intertidal and subtidal zones, coral reefs, salt marshes and the open ocean) often contain a characteristic and restricted diversity of forms which may differ markedly from season to season and from one geographical location to another (1,2).

This is particularly evident in the open ocean where only a few genera and species have been shown to occur abundantly and to be important components of the phytoplankton community. Principle among these are marine representatives of the genera Synechococcus, Synechocystis, Trichodesmium and Richellia. By contrast, the diversity of freshwater planktonic forms is much more extensive, encompassing over 100 species, 20 of which are capable of forming extensive water blooms (3). This is probably due in part to the fact that freshwater planktonic habitats are diverse ranging from oligotrophic to highly eutrophic environments. The open oceans are relatively oligotrophic and the cyanobacteria that occur there reflect this in their growth requirements and sensitivities.

Marine representatives of the genus Synechococcus (sensu Rippka et al., 1979) (4) are small unicellular forms (0.6 x 1.4 μm) that are abundant within the euphotic zone of the world's temperate and tropical oceans (5,6). Marine representatives of the genus Synechocystis (sensu Rippka et al., 1979) (4) are novel unicellular forms capable of aerobic nitrogen fixation that have been isolated from the tropical Atlantic (7). Members of the genera Trichodesmium and Richellia are filamentous forms found in the tropical oceans that are capable of nitrogen fixation (2). Trichodesmium spp. are free living nonheterocystous forms, whereas Richellia spp. occur principally as intracellular symbionts in several species of diatoms (2).

The general principles of isolation and growth for cyanobacteria that are discussed elsewhere in this volume and in more detail in (8) are also applicable to marine planktonic forms.

In press: Methods in Enzymology.

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WHOI Contribution No. 6439.

## SODIUM-COUPLED MOTILITY IN A SWIMMING CYANOBACTERIUM

Joanne M. Willey, John B. Waterbury and E. Peter Greenberg

The energetics of motility in Synecho-

coccus WH8113 were studied to understand better the unique non-flagellar swimming of this cyanobacterium. There was a specific sodium requirement for motility such that below 10 mM external sodium, cells were immotile and above 10 mM, cell speed increased with increasing sodium levels to a maximum of about 15 μm/s at 150-250 mM sodium. The sodium motive force increased similarly with increasing external sodium from -120 mV to -165 mV but other energetic parameters including proton motive force, electrical potential, the proton diffusion gradient, and the sodium diffusion gradient did not show such a correlation. Over a range of external sodium concentrations, cell speed was greater in alkaline environments than in neutral or acidic environments. Monensin and CCCP inhibited motility and affected components of sodium motive force but did not affect ATP levels. Cells were motile when incubated with DCMU and arsenate which decreased cellular ATP to about 2% of control values. The results of this investigation are consistent with the conclusion that the direct source of energy for Synechococcus motility is a sodium motive force and that below a threshold of about - 100 mV, cells are immotile.

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WHOI Contribution No. 6423.

## PHYSIOLOGY AND BIOCHEMISTRY

### KNUDSEN-TRANSITIONAL FLOW AND GAS PRESSURIZATION IN LEAVES OF NELUMBO

John W.H. Dacey

Pressures in gas spaces in leaves of the lotus Nelumbo are higher than ambient pressure. The pressurization capacity of leaves was studied as a function of leaf temperature, and the composition of air entering evacuated leaves was used to calibrate the pore sizes which determine flow in these leaves. The adaxial side of the leaf of Nelumbo has two distinct regions in terms of gas exchange characteristics. There is a region of relatively high mean pore diameter in the center of the leaf opposite the point of petiole insertion. Gas exchange between the remainder of the leaf (>99% by area) and the atmosphere is restricted by "pores" with an effective mean diameter less than 0.03 μm. As a result, a flowthrough ventilation operates in each leaf. Air enters the leaf across the expanse of the lamina, and escapes back to the atmosphere through the highly porous region at the center of the lamina.

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WHOI Contribution No. 6411.

### VARIATION AMONG TOXIC DINOFLAGELLATES FROM THE NORTHEASTERN UNITED STATES AND CANADA I. ENZYME ELECTROPHORESIS

Barbara A. Hayhome, Donald M. Anderson, David M. Kulis and Diane J. Whitten

Relationships among toxic and non-toxic dinoflagellates of the genus Alexandrium (= Protogonyaulax) from Long Island, New England, and northeastern Canada were investigated using enzyme electrophoresis. A high degree of similarity among toxic isolates was observed despite large geographic separations of source populations. This high degree of similarity is in marked contrast to observations on toxic members of this genus from the west coast of Canada and the United States and supports the proposal that dispersal of toxic strains in the east from a common source has occurred recently, presumably from established populations in northern Maine or Canada. Non-toxic strains appeared to be from isolated endemic populations. Furthermore, a characteristic enzyme banding pattern multiplicity that is likely to be chloroplast-encoded was observed only among toxic isolates.

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WHOI Contribution No. 6613.

### INDUCTION OF CYTOCHROME P-450 IN Fundulus heteroclitus: ENZYME ACTIVITY, IMMUNOCHEMICAL AND NUCLEIC ACID STUDIES

Pamela J. Kloepper-Sams and John J. Stegeman

Cytochrome P-450 induction is a known response of marine organisms to chemical exposure, yet the mode of this induction is not known for any marine species. This

study was undertaken to evaluate hepatic P-450 content, catalytic activity and mRNA levels in Fundulus heteroclitus after exposure to the 3-methylcholanthrene-type inducer ß-naphthoflavone (BNF). Ethoxyresorufin O-deethylase (EROD) activity was significantly increased after BNF treatment, although hepatic microsomal P-450 levels were unchanged. However, the proportion of P-450 which cross-reacted with an anti-scup P-450E monoclonal antibody on immunoblots was low in control animals and increased dramatically in the BNF-treated animals. In vitro translation products of liver RNA were immunoprecipitated with an anti-P-450E polyclonal antibody. Flurograms of the immunoprecipitated products separated by gel electrophoresis resulted in no detectable signal from the control groups, while the BNF group showed incorporation of $[^3H]$-leucine in a single band with a $M_r$ of 56,000 daltons. This study provides evidence that, as in mammalian systems, the induction of P-450 by MC-type inducers in fish is under transcriptional control.

In press: Marine Environmental Research.

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WHOI Contribution No. 6628.

## ASSESSMENT OF CIGUATERA DINOFLAGELLATE POPULATIONS: SAMPLE VARIABILITY AND ALGAL SUBSTRATE SELECTION

Phillip S. Lobel, Donald M. Anderson and Monique Durand-Clement

Preliminary assessment is made of two key components in ciguatera ecology. First, we examined the numerical variability of Gambierdiscus toxicus as an epiphyte on the macroalgae, Dictyota and Galaxaura. Variability is examined by a statistical bootstrap technique to determine the minimum number of samples required to adequately estimate the abundance of G. toxicus at one station and to test for statistically significant difference between two stations. A minimum of ten replicates was needed at the relatively low G. toxicus abundance found at our study site. Second, we demonstrated the feasibility of conducting controlled laboratory experiments to assess the short-term colonization behavior of G. toxicus on selected macroalgae offered in varying mass and surface area ratios. In order to assess G. toxicus abundance and distribution, the number of cells per unit of host alga must be standardized. We show that contradictory conclusions can be reached depending on whether the number of dinoflagellate cells is normalized to algal biomass or surface area.

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WHOI Contribution No. 6614.

## LIPID COMPOSITION OF THE DIGESTIVE GLANDS OF Mytilus edulis AND Carcinus maenas IN RESPONSE TO CONTAMINANT GRADIENTS

Judith McDowell Capuzzo and Dale F. Leavitt

In field studies in Langesundsfjord, Norway, changes in lipid content and lipid:protein ratios of digestive glands of Mytilus edulis and Carcinus maenas were reflected along the pollution gradient with populations of Mytilus showing elevations in both parameters at the three most contaminated stations (Stations 2, 3, and 4) in comparison to the reference site (Station 1) and populations of Carcinus showing elevations only at Station 3. In mesocosm experiments only Mytilus from the high dose basin showed elevations in lipid content and lipid:protein ratios; Carcinus in the medium dose basin showed a decrease in both parameters.

Analysis of lipid class composition for field and mesocosm populations of Mytilus reveal differences in lipid class distributions in response to contaminant gradients that reflect alterations in mobilization of triacylglycerols to phospholipid pools, reductions in phospholipid content, and nutritional condition. Changes in lipid class distributions of Mytilus from both field and mesocosm experiments are consistent with observations of histological and histopathological changes and correlate well with body burden data for tissue concentrations of aromatic hydrocarbons and/or polychlorinated biphenlys.

Lipid class distributions of field populations of Carcinus indicate alterations in the mobilization of triacylglycerols, sterol turnover, and reductions in phospholipid content. Responses to the contaminant gradient are consistent with observations of changes in respiration rate and elevations in glutathione transferase activity and populations of crabs from station 3 appear to be the most impacted. The responses are not consistent with body burden data of aromatic hydrocarbons nor with the trends observed in PCB concentrations that indicate the highest concentration of PCBs at station 4. Crabs from mescocosm experiments show no evidence of alterations in lipid class distribution in spite of a consistent trend in aromatic hydrocarbon tissue concentrations along the gradient. Differential responses of field and mescosm

populations of Mytilus and Carcinus are possibly the result of metabolic capacity for detoxification and differences in trophic transfer.

In press: Marine Ecology Progress Series.

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WHOI Contribution No. 6579.

## EFFECTS OF TOXIC CHEMICALS IN THE MARINE ENVIRONMENT: PREDICTIONS OF IMPACTS FROM LABORATORY STUDIES

Judith McDowell Capuzzo, Michael N. Moore and John Widdows

The degree to which toxicity testing can lead to predictions of long-term environmental consequences of contaminant exposure has been widely debated. Laboratory approaches designed to address both chemical concerns of contaminant bioavailability and persistence in addition to biological concerns of sublethal effects on marine organisms would be most useful in providing the linkage between laboratory and field evaluations. Examples of bioenergetic, developmental, and reproductive abnormalities observed with exposure to lipophilic organic contaminants are discussed in reference to consequences at higher levels of biological organization. Alterations in bioenergetics linked with observations of reduced fecundity and viability of larvae, abnormalities in gamete and embryological development, and reduced reproductive effort provide a strong empirical basis for examination of population responses. Such empirical data can be incorporated into population models to assess the effects of energetic, reproductive and developmental aberrations on population success and provide the basis for further examining the predictive value of toxicity testing.

In press: Aquatic Toxicology.

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WHOI Contribution No. 6580.

## IDENTIFICATION OF A C-KI-RAS ONCOGENE IN A NEOPLASM ISOLATED FROM WINTER FLOUNDER

Gerald McMahon, J. Julie Huber, John J. Stegeman and Gerald N. Wogan

It has been shown that a high incidence of hepatomas are present in winter flounder (P. americanus) obtained from Boston Harbor. It has been suggested that this may be a consequence of locally high levels of polycyclic aromatic hydrocarbons found in the sediment. The purpose of this study was to determine whether transforming DNA sequences (oncogenes) could be identified in liver neoplasms isolated from feral fish and to study their relationship to their corresponding protooncogenes. The ultimate aim of this study is to characterize novel mutations in oncogenes derived from these hepatomas to correlate these genetic changes with chemical exposure history. Genomic DNA was isolated from liver neoplasms and transfected into NIH3T3 mouse fibroblasts to assay for the formation of transformed foci. DNA was prepared from transformed foci and analyzed by Southern blot hybridization to viral DNA probes specific for c-Ki-ras and c-Ha-ras DNA sequences. A ci-Ki-ras oncogene was identified in a transformant derived from one of the two tumors assayed. Comparison of c-KI-ras DNA sequences of tumor and tumor-derived transformants indicate that the activated oncogene in the transformant is of flounder origin. We are currently analyzing the flounder oncogene for activitating point mutations by primer-directed enzymatic amplification and direct sequence analysis.

In press: Marine Enviornmental Research.

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WHOI Contribution No. 6629.

## IMMUNOHISTOCHEMICAL LOCALIZATION OF CYTOCHROME P-450E IN LIVER, GILL AND HEART OF SCUP (Stenotomus chrysops) AND RAINBOW TROUT (Salmo gairdneri)

Michael R. Miller, David E. Hinton, James J. Blair and John J. Stegeman

Monoclonal antibody directed against a major ß-napthoflavone (BNF)-induced form of teleost cytochrome P-450, P-450E (equivalent to P-450c in rat) was used to immunolocalize this enzyme in liver, gill and heart of scup and trout. Liver sections from both species showed P-450E in the cytoplasm of hepatocytes. No regional differences were observed which might indicate zonation of cytochrome P-450E within subpopulations of hepatocytes. Scup exocrine pancreatic cells were only weakly positive. In the gill of both fish, cytochrome P-450E was restricted to the endothelium (pillar

cells) of secondary lamellae, where fluorescence appeared as a chain in longitudinal sections through lamellae and as star-shaped clusters in en face views. Sections of ventricular wall in both species revealed P-450E was restricted to endothelium at margins of muscle bands limiting heart ventricular lumen. Localization in the specific cells of these and other organs may be fundamentally important in understanding the role of cytochrome P-450E.

In press: Marine Environmental Research.

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WHOI Contribution No. 6632.

## STIMULATION OF GONADAL STEROIDOGENESIS IN FUNDULUS HETEROCLITUS BY RECOMBINANT SALMON GROWTH HORMONE

Hanuman Singh, Robert W. Griffith, Akiyoshi Takahashi, Hiroshi Kawauchi, Peter Thomas and John J. Stegeman

The effects of the recombinant salmon growth hormone (sGH) on plasma sex steroid levels and gonadal function were investigated in hypophysectomized Fundulus heteroclitus. Effects of sGH were compared to those of purified chum salmon prolactin (sPRL), Atlantic salmon gonadotrophin (sGTH) and salmon pituitary extract (sPE). Treatment with sGH significantly increased plasma concentrations of testosterone in males and estradiol-17ß in females; sPRL had similar effects on testosterone levels in males. Further treatment with these hormones prevented the decline in gonadal weight observed after hypophysectomy in both males and females. In vivo treatment of male fish with sGH also augmented testosterone and 11-ketotestosterone production by testis tissue subsequently incubated in vitro. Direct action(s) on gonadal steroidogenesis were examined by incubating gonadal tissues from hypophysectomized fish in vitro with various hormones. sGH significantly stimulated the in vitro production of testosterone and 11-ketotestosterone by testis, and estradiol-17ß by ovary. sPE and sGTH also stimulated gonadal steroidogenesis, whereas sPRL and bGH had no significant effect. By comparison, rainbow trout gonads also produced increased amounts of steroids when treated with sGH in vitro. The use of a cloned GH rules out contamination by other pituitary hormones. These results, therefore, demonstrate that recombinant salmon growth hormone possesses steroidogenic and gonadotropic activity. Purified sPRL may also have steroidogenic and gonadotropic actions. However, the significance of these effects of teleost GH or PRL is not yet known.

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WHOI Contribution No. 6630.

## APPARENT CYTOCHROME P-450 INDUCTION AS AN INDICATION OF EXPOSURE TO ENVIRONMENTAL CHEMICALS IN THE FLATFISH Platichthys flesus

John J. Stegeman, Bruce R. Woodin and Anders Goksoyr

Flounder (Plathicthys flesus) from a pollution gradient in Frierfjord, Norway, are experimentally exposed to petroleum oil in mesocosm basins, were analyzed for evidence of specific cytochrome P-450 induction. Ethoxyresorufin O-deethylase (EROD) activity and the content of microsomal cytochrome P-450 in liver were positively correlated with residues of PAH and PCB in mussels at four field sites. Monoclonal antibody 1-12-3 to the PAH- and PCB-inducible scup P-450 isozyme (P-450E) recognized a single protein band in P. flesus liver microsomes. The amount of this protein correlated positively with levels of EROD activity and microsomal P-450 content in the field-sampled fish. By contrast, fish from control or treated mesocosms all possessed relatively low levels of EROD activity and immunodetected protein. Levels of high molecular weight PAH known to induce teleost P-450 were likewise low in these basins, although there was a high content of other aromatics. We conclude that both EROD activity and levels of the P. flesus counterpart to P-450E indicate induction by environmental chemicals in P. flesus from Frierfjord.

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WHOI Contribution No. 6631.

## INDUCTION OF MONOOXYGENASE ACTIVITY IN THE INTESTINE OF SPOT (Leiostomus xanthurus), A MARINE TELEOST, BY DIETARY PAH

Peter A. Van Veld, John J. Stegeman, Bruce R. Woodin, John S. Patton and Richard F. Lee

The response of intestinal monooxyganases to dietary polycyclic aromatic hydrocarbon (PAH) exposure was evaluated in spot (Leiostomus xanthurus), a marine teleost fish. Ethoxyresorufin O-deethylase (EROD) and aryl hydrocarbon hydroxylase (AHH) were highest in the pyloric caeca and in the proximal half of the intestine. Intestinal microsomes from fish given control diets had very low levels of EROD and AHH activities relative to those in liver. Following exposure to a diet containing a 10 mg 3-methylcholanthrene/kg food, the levels of intestinal EROD and AHH activities increased 36-fold and 17-fold respectively, such that intestinal monoxygenase activity exceeded that of the liver, which was not induced by this treatment. A significant increase in intestinal monoxygenase activity occurred in fish receiving dietary benzo[a]pyrene (BP) at concentrations as low as 10 µg BP/kg food. A 5-fold increase in intestinal AHH and EROD activities was observed within three hours after administration of dietary BP. A plateau in gut monooxygenase activity occurred after approximately three days of PAH exposure; these activities decreased to control levels within three days after replacing the PAH diet with the control diet. Starvation resulted in disappearance of detectable monooxygenase activity. Monoclonal antibody (MAb 1-12-3) against the major PAH-inducible cytochrome P-450 (P-450E) in the liver of the marine teleost (Stenotomus chyrsops) (Park et al., 1986, Arch. Biochem. Biophys. 249: 339-350) recognized a single protein band in intestinal microsomes, with $M_r$ near 54K, which we conclude is the spot counterpart to cytochrome P-450E. The presence and activity of PAH-inducible cytochrome P-450 of spot intestine appeared to be almost entirely dependent upon dietary PAH exposure. The results indicate that the fish intestinal monooxygenase system can play a major role in the metabolism of dietary PAH.

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WHOI Contribution No. 6619.

## P H Y T O P L A N K T O N

### TOXIC ALGAL BLOOMS AND RED TIDES: A GLOBAL PERSPECTIVE

Donald M. Anderson

The literature on toxic algal blooms and red tides documents a global increase in the frequency, magnitude, and geographic extent of these events over the last two decades. Some of this increase is undoubtedly a result of the increased awareness and analytical capabilities of the scientific community, but a strong correlation between the number of red tides and the degree of coastal pollution or utilization of coastal waters for aquaculture argue that there are other contributing factors. It also appears likely that toxic algal species have spread within regions over spatial scales of hundreds of kilometers, moving with major water currents and storms. Long distance transport of species across oceans may have occurred as well, but the evidence is not conclusive and the hypothesis controversial.

In press: First International Symposium on Red Tides.

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WHOI Contribution No. 6669.

### THE UNIQUE, MICRORETICULATE CYST OF THE NAKED DINOFLAGELLATE, Gymnodinium catenatum Graham

Donald M. Anderson, Dean M. Jacobson, Isabel Bravo and John H. Wrenn

Gymnodinium catenatum Graham is an unarmored dinoflagellate responsible for episodes of paralytic shellfish poisoning. This species forms a resting cyst that is unique in several ways. The outer surface of the spherical, brownish cyst is microreticulate, composed of hundreds of 1-3 µm polygons which, in several regions, are smaller, more uniform in shape, and oriented in distinct bands that outline morphological features. These characteristics on the cyst reflect the cingulum, sulcus, flagellar pore complex, and acrobase of the motile stage precursor to the cyst. Elsewhere on the cyst, the ornamentation is randomly distributed. The archeopyle is irregularly but extensively developed. Its margin is generally smooth and extends almost completely around the circumference of the cyst, though not consistently in the plane of the equator. The cyst wall is resistant to acetolysis and standard palynological preparation techniques.

The significance of this cyst is that it is the first described cyst of a naked dinoflagellate that bears oriented surface ornamentation reflecting features of the motile dinoflagellate. Its microreticulate surface ornamentation is unique to dinocysts, naked or armored, living or

fossilized. Resistance of the cyst wall to harsh processing techniques suggests the presence of sporopollenin-like material commonly associated with the cysts of armored dinoflagellates. From an ecological standpoint, the existence of a G. catenatum cyst has important implications with respect to the species bloom dynamics and geographic distribution. In addition, the distinct differences between this cyst and those of the armored saxitoxin-producing gonyaulacoid species argues against a proposed evolutionary linkage.

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WHOI Contribution No. 6474.

## CHAIN FORMING DINOFLAGELLATES: AN ADAPTATION FOR RED TIDE FORMATION

Santiago Fraga and Donald M. Anderson

Swimming speeds of two chain-forming dinoflagellates, the toxic Gymnodinium catenatum and the non-toxic Protogonyaulax affinis, were measured as a function of chain lengths. Long chains swam faster than short chains. The increase in speed from a single cell to a chain of four cells for both species was about a factor of 1.5-1.6. Populations of both dinoflagellate species were conicident with red tides in areas of coastal upwelling relaxation and downwelling in the Ria de Vigo, northwest Spain. The higher swimming speeds of long chains may allow more cells to remain in the photic zone during downwellings or convergences. This may be a mechanism for local concentration of cells leading to a red tide.

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## INFLUENCE OF UPWELLING RELAXATION ON DINOFLAGELLATES AND SHELLFISH TOXICITY IN RIA DE VIGO, SPAIN

Santiago Fraga, Donald M. Anderson, Isabel Bravo, Beatriz Reguera, Karen A. Steindinger and Clarice M. Yentsch

Outbreaks of paralytic shellfish poisoning (PSP) along the northwest coast of Spain have become a serious threat to the extensive mussel farming industry in that region over the last decade. During the summer, high phytoplankton productivity is supported by the sustained upwelling of nutrient-rich deep water into the rias. A PSP episode in the fall, 1985 in Ria de Vigo coincided with the sudden appearance, rapid numerical increase, and dominance of two chain-forming dinoflagellates, Gymnodinium catenatum and Protogonyaulax affinis. Field data suggest that warm offshore surface water was transported into the ria as the summer upwelling ceased. This occurred when winds changed from northerly (upwelling favorable) to southerly or westerly (upwelling unfavorable); the injected water contained established populations of oceanic and neritic dinoflagellates. The simultaneous appearance and dominance of two dinoflagellates that form long chains leads us to speculate that the small-scale downwelling of water within the ria favored efficient swimmers among the phytoplankton. These data not only implicate these two species as possible sources of the PSP toxins in local mussels, but they also suggest the feasibility of developing a bloom prediction capability for some dinoflagellate species based in part on an upwelling index that can indicate when offshore surface waters might be forced into the rias.

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WHOI Contribution No. 6461.

## PHOTOSYNTHETIC RESPONSE OF Gonyaulax tamarensis DURING GROWTH IN A NATURAL BLOOM AND IN BATCH CULTURE

Patricia M. Glibert, Todd M. Kana and Donald M. Anderson

We investigated the photosynthetic behavior of the dinoflagellate Gonyaulax tamarensis at various stages during growth in a natural bloom in Salt Pond, Massachusetts, and in laboratory cultures. Photosynthetic capacity ($P_{max(cell)}$), determined using a single-cell isolation technique, increased from 0.25 to 0.32 ng C $cell^{-1}h^{-1}$ during bloom development, then dropped sharply to 0.19 ng C $cell^{-1}h^{-1}$ a few days prior to bloom decline. For G. tamarensis cultures grown to nitrogen depletion, both $P_{max(cell)}$ and $\alpha_{(cell)}$

decreased several-fold as soon as $NO_3^-$ in the media fell to zero. Several lines of evidence are presented that suggest that nitrogen limitation played an important role in the decline of the G. tamarensis bloom despite the fact that ambient nitrogenous nutrient concentrations did not become depleted in the pond.

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WHOI Contribution No. 6586.

## EFFECTS OF LIGHT AND NITROGEN LIMITATION ON THE CELL CYCLE OF THE DINOFLAGELLATE Amphidinium carteri

Robert J. Olson and Sallie W. Chisholm

Cell cycle phase durations of cultures of Amphidinium carteri in light- or nitrogen-limited balanced growth were determined using flow cytometry. For both types of growth rate limitation, the increases in generation time caused by increasing degrees of limitation were due solely to expansion of the $G_1$ phase of the cell cycle. The durations of the S and $G_2$+M phases were independent of growth rate. Furthermore, when cells were deprived completely of light and nitrogen, they arrested in the $G_1$ phase of the cell cycle. The results indicate that light- and nitrogen-dependent processes are heavily concentrated in the early part of the cell cycle, while DNA replication and cell division, once initiated, are independent of light or N supply.

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WHOI Contribution No. 6689.

## FLOW CYTOMETRY: APPLICATIONS AND PROSPECTS

Robert J. Olson and Sallie W. Chisholm

The ideal way to study populations is to examine each individual in the population. This is obviously impractical for samples using traditional microscopical methods, so oceanographers have compromised by using microscopes to study a very small proportion of the individuals, and using bulk sampling techniques, such as filtration, to measure the biomass and physiological rate processes of the community as a whole. The labor-intensive nature of microscopy precludes its widespread use, and bulk measurements obscure all information regarding distributions of properties within the population, since these methods average the properties. Many of the properties of plankton are not normally distributed among individuals, so information obtained from averaged values is almost surely giving us a distorted view of the sestonic ecosystem.

Flow cytometry represents an alternate compromise between the desirability of individual analyses and requirements for analysis of large populations. This technique allows the simultaneous measurement of several optical characteristics (chiefly fluorescence and light scattering) of individual particles as small as 0.3 μm in diameter. Analysis rates can be as high as several thousand particles per second, and the instrument can also physically sort particles out of a sample, based on predetermined combinations of optical properties. Flow cytometry was developed as a biomedical research tool and has been principally used to study cell kinetics and to develop diagnostic tests. Detailed reviews of principles and applications of flow cytometry to these fields can be found in Melamed et al. (1979), Shapiro (1983, 1985), and Van Dilla et al. (1985). In the past several years oceanographers have begun to explore this technology as well (Yentsch et al. 1983, Olson et al. 1985). In this chapter we will describe the basics of flow cytometry technology, outline the present state of oceanographic applications of flow cytometry, and discuss some promising potential applications. We will also discuss practical aspects of the use of flow cytometry in oceanography, noting some of the limitations of this technology and approach to the study of marine systems.

In press: Photosynthesis in the Sea, R. Alberte [Ed], Oxford Press.

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WHOI Contribution No. 6690.

## ANALYSIS OF Synechococcus PIGMENT TYPES IN THE SEA USING SINGLE AND DUAL BEAM FLOW CYTOMETRY

Robert J. Olson, Sallie W. Chisholm, Eric R. Zettler and Elizabeth V. Armbrust

Distributions and optical properties of Synechococcus cells were studied at sea using flow cytometric techniques to distinguish between several different pigment types. Cells with only phycoerythrobilin chromophores were distinguished from those with both phycoerythrobilin and phycourobilin (PUB) chromophores by exciting with 488 nm light and measuring the resulting phycoerythrin fluorescence below 560 nm (green) and above 560 nm (orange). All populations detected had green/orange emission ratios similar to PUB-containing strains of Synechococcus in culture. In addition, the ratio of fluorescence emission intensity resulting from excitation at 488 nm and 515 nm was used to measure the relative PUB content of the cells. In the majority of samples, we found ratios as high or higher than those of the cultured strains considered to have unusually high PUB contents.

These findings suggest that our perception of the characteristics of Synechococcus populations in the open ocean may have been biased by studies of cells from culture collections. According to our survey, virtually all Synechococcus cells in the open ocean contain PUB and most of them have very high relative PUB contents. This gives them absorption properties not very different from those of the eukaryotic phytoplankton, and thus could explain why photosynthetic action spectra have suggested that light absorption by phycoerythrobilin-rich phycoerythrin (at about 550 nm) is relatively unimportant in the open ocean.

In press: Deep Sea Research.

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WHOI Contribution No. 6667.

## EFFECTS OF ENVIRONMENTAL STRESSES ON THE CELL CYCLE OF TWO MARINE PHYTOPLANKTON SPECIES

Robert J. Olson, Daniel Vaulot and Sallie W. Chisholm

Cell cycle phase durations of cultures of Hymenomonas carterae Braarud and Fagerl, a coccolithophore, and Thalassiosira weissflogii Grun., a centric diatom, in temperature-, light- or nitrogen-limited balanced growth were determined using flow cytometry. Suboptimal temperature caused increases in the duration of all phases of the cell cycle (though not equally) in both species, and the increased generation time of nitrogen-limited cells of both species was due almost wholly to expansion of $G_1$ phase. In H. carterae light limitation caused only $G_1$ phase to expand, but in T. weissflogii both $G_2$+M and $G_1$ were affected. These results are discussed in relation to cell division phasing patterns of these two species and to models of phytoplankton growth.

Simultaneous measurements of protein and DNA on individual cells indicated that under all conditions, the protein content of cells in $G_1$ was a constant proportion of that of $G_2$+M cells. Simultaneous measurements of RNA and protein on each cell indicated that the amounts of these two cell constituents were always tightly correlated. Under conditions of nitrogen limitation both protein and RNA per cell decreased to less than one-third of the levels found in non-limited cells. This indicates, at least for nitrogen-replete cells, that neither protein nor RNA levels are likely to act as the trigger for cell cycle progression. Strict control by cell size is also unlikely since mean cell volume decreased as growth rates were limited by light and nitrogen supply, but increased with decreasing temperature.

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WHOI Contribution No. 6692.

## PATTERNS OF INDIVIDUAL CELL GROWTH IN MARINE CENTRIC DIATOMS

Robert J. Olson, Carl Watras and Sallie W. Chisholm

Rates of cell volume increase in individuals of five genera of centric marine diatoms were measured using time-lapse video microscopy. In continuous light, size increased continuously in Thalassiosira weissflogii and Lauderia borealis, while "steps" were observed during the growth of Stephanopyxis turris, Biddulphia aurita and Coscinodiscus sp. In the latter

species, the duration of the periods of "no growth" were well-correlated with the generation time for individual cells. When the species exhibiting continuous growth in constant light were grown on L:D 12:12, the rate of size increase during the dark period was on average slower than during the light. Behavior of individual cells was highly variable, however, and in L. borealis appeared to be related to the previous light history of each cell. The results suggest a regulatory coupling between the cell cycle and the time evolution of cell volume.

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WHOI Contribution No. 6691.

## P L A N K T O N  E C O L O G Y

### LOCOMOTORY PATTERNS OF THE PLANKTONIC CILIATE Favella SP.: ADAPTATIONS FOR LOCATING FOOD PATCHES AND FOOD PARTICLES

Edward J. Buskey and Diane K. Stoecker

Using a video computer system for motion analysis, we documented changes in the kinetic behavior of the tintinnid, Favella sp., in response to changes in food concentration. Favella transiently reduces its swimming speed and increases its turning behavior in response to increases in food density. Similar changes in swimming pattern are observed when chemosensory or mechanosensory stimuli associated with Favella's preferred food, dinoflagellates, are increased. These kinetic responses should contribute to the aggregations of this tintinnid that are observed in microscale (< 1 m) and fine scale (m to 100's of m) patches of dinoflagellates.

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WHOI Contribution No. 6469.

### COMPONENTS OF THE ZOOPLANKTON PRODUCTION CYCLE IN THE TEMPERATE OCEAN

Cabell S. Davis

Components of the zooplankton production cycle (assimilation, respiration, and predation) on Georges Bank were analyzed using three models of increasing complexity, i.e., total biomass (Riley, 1947), size-structure (Huntley and Boyd, 1984) and species population (Davis, 1984a). Other temperate marine areas with seasonal cycles in temperature similar to Georges Bank were identified and available data on zooplankton biomass and species cycles were found. For Georges Bank, the species level model, based on well-defined empirical relationships between temperature, development rate, and fecundity, revealed that highest production occurs by small animals during warmest months (e.g., September), when biomass is low. By contrast, the total biomass model calculated maximum production during June, coinciding with peak herbivore mass, but could not account for high fall production because size-dependent effects were not considered. The size-structured model computed high fall production rates but greatly overestimated June production by failing to consider life-history characteristics of component species (i.e., diapause in Calanus). In general, it was found that the temperature cycle has a much greater influence on production rates than does food concentration. Zooplankton cycles from the North Sea, Japan Sea, and Argentinian Shelf were similar to Georges Bank, suggesting that the modeling results may be generally true for temperate areas having large annual ranges in temperature (> 10°C). The traditional view that temperate zooplankton production is primarily food-limited and occurs mainly during spring/summer coinciding with peak herbivore stock can no longer be considered valid. Instead the cycle appears largely driven by temperature so that production is highest during summer/fall when biomass is low and small warm-water species dominate. The misconception of the production cycle has resulted from use of oversimplified models.

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WHOI Contribution No. 6410.

### ALGAL-FORAMINIFERAL SYMBIOSIS IN THE PLANKTONIC FORAMINIFER Globigerinella aequilateralis; I. OCCURRENCE AND STABILITY OF TWO MUTUALLY EXCLUSIVE ENDOSYMBIONTS AND THEIR ULTRASTRUCTURE

Walter W. Faber, Jr., O. Roger Anderson, Judith L. Linsey and David A. Caron

We have observed two ultrastructurally distinct endosymbiotic algae in the cytoplasm of the planktonic foraminifer Globigerinella aequilateralis. Based on their fine structure we classify both algal types as Chrysophycophytes. Both species of algae formed highly stable, and mutually exclusive, associations which persisted in laboratory culture throughout the vegetative growth period of the foraminifer. However, a daily photoperiod was required to prevent symbiont digestion by the host. Symbiont density increased in the foraminiferal cytoplasm as foraminiferal size increased for foraminifera placed in a normal light/dark cycle and offered particulate food (brine shrimp nauplii). Starved specimens in the light digested some of their symbionts but many algae were still present in the cytoplasm after six days of starvation. In contrast, foraminifera kept in continuous darkness rapidly digested their symbionts over the six day period even when offered particulate food. We conclude that symbiont productivity is essential for maintaining the stability of the algal-foraminiferal association. This is the first study to report more than one species of algae as suitable endosymbionts in a single species of planktonic foraminifera.

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WHOI Contribution No. 6705.

## ALGAL-FORAMINIFERAL SYMBIOSIS IN THE PLANKTONIC FORAMINIFER Globigerinella aequilateralis; II. EFFECTS OF TWO SYMBIONT SPECIES ON FORAMINIFERAL GROWTH AND LONGEVITY

Walter W. Faber, Jr., O. Roger Anderson, and David A. Caron

Two endosymbiotic algal associations (designated Type I and II) of the planktonic foraminifer Globigerinella aequilateralis were cultured in the laboratory under three light and three feeding regimes in order to investigate the effect of symbiont type on the life processes (growth rate, test size, gametogenic potential) of the host. Overall, average final test sizes were consistently greater for groups of Type I foraminifera except for specimens which received no particulate food. In addition, both the light and feeding regimes had effects on foraminiferal growth and reproduction which were apparently due to symbiont type. For specimens receiving particulate food (brine shrimp nauplii), foraminifera with Type I symbionts had longer survival times and slower rates of chamber formation in a high light intensity (100-200 $\mu E\ m^{-2}\ sec^{-1}$) than Type II specimens cultured under the same conditions. These differences were less dramatic for specimens cultured in a low light intensity (20-50 $\mu E\ m^{-2}\ sec^{-1}$) and were not apparent for specimens cultured in continuous darkness. For specimens which were cultured at low light intensity but were not fed, foraminifera with Type I symbionts formed very few chambers and gradually starved without undergoing gametogenesis. In contrast, foraminifera with Type II symbionts were able to grow at least one chamber and produced gametes. We conclude that the type of endosymbiont can significantly affect the life processes of the foraminiferal host, and thereby its success in a particular environment.

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WHOI Contribution No. 6703.

## CARBON AND NITROGEN UPTAKE AND $NH_4^+$ BY PELAGIC MICROPLANKTON AND MARINE SNOW FROM THE NORTH ATLANTIC

Patricia M. Glibert, Mark R. Dennett and David A. Caron

Comparative rates of carbon and nitrogen uptake, and nitrogen regeneration associated with plankton size fractions and diver-collected marine snow particles were determined in the Sargasso Sea and Gulf Stream during May 1982. Rates of total nitrogen uptake of Sargasso Sea phytoplankton exceeded those of the Gulf Stream phytoplankton by factors ranging from 1.8 to 5.6. Rates of $NH_4^+$ regeneration by plankton size fractions equaled or exceeded rates of $NH_4^+$ uptake in the Sargasso Sea, but in the Gulf Stream were negligible in all but one case. Sufficient marine snow was collected in the Gulf Stream on four occasions to permit measurements of nitrogen uptake and regeneration; the density of marine snow in the Sargasso was too low for these measurements. The rates of $NH_4^+$ uptake ($\mu g\ atom\ l^{-1}\ h^{-1}$) of the snow material exceeded those of the surrounding water by 600-> 1700 times. In all but one case, the regeneration rates of $NH_4^+$ associated with snow exceeded those of $NH_4^+$ uptake. Rates of $NO_3^-$ and urea uptake by the snow were less than half those of $NH_4^+$. Bacterial densities and production and protozoan densities were enumerated on aliquots of the same snow particles; enrichment factors of the cultivable ciliates and flagellates were 6500-9000 relative to ambient seawater, but bacterial populations were only moderately enriched on marine snow, and production rates were lower than in free-living bacteria. The large bacterivorous population may explain the relatively low

concentrations of bacteria and likely accounted for a substantial fraction of the $NH_4^+$ regeneration. Thus, marine snow appeared to be an important site for $NH_4^+$ regeneration in these Gulf Stream waters.

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WHOI Contribution No. 6704.

## SPATIAL AND TEMPORAL DISCONTINUITIES OF BIOLOGICAL PROCESSES IN PELAGIC SURFACE WATERS

Joel C. Goldman

The classical paradigm of an unproductive, nutrient-poor pelagic zone where primary production is fueled almost exclusively by nutrient regeneration processes, appears at odds with the contemporary view that new primary production, supported by a stoichiometric input of oxidized nutrients into the euphotic zone, is considerably higher than previously thought. One way to accommodate both scenarios is to invoke the two layer concept in which the bulk of new primary production occurs at or near the base of the euphotic zone in response to pulsed injections of $NO_3^-$ and $PO_4^{-3}$. Productivity in the upper euphotic zone where nutrients and biomass are trapped would be regulated almost exclusively by regenerative and degradative processes that occur within the microbial food loop. Since the microbial food loop which consists of a tightly-knit assemblage of phototrophic and heterotrophic nano and picoplankton persists throughout the euphotic zone, most of the energy and carbon processed by these small microbes would be lost through respiration and thus would not contribute to new production exiting to deeper waters. This raises the perplexing question of how biological processes are coupled to the input of new nutrients which, in turn, is controlled by physical events that occur on greatly varying temporal and spatial scales. Possibly, short-lived, local mixing events provide the right combination of light and new nutrients to allow rapid and undetected bursts of growth of larger phytoplankton species, in effect, creating ephemeral eutrophication zones. The resulting food chain may be short and simple so that newly fixed carbon can exit the euphotic zone rapidly while leaving behind an oxygen signal.

In press: In: "Towards a theory on biological and physical interactions in the world ocean." Ed. by Brian J. Rothschild, D. Reidal Publishing Company.

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WHOI Contribution No. 6545.

## MEASUREMENT OF PHOTOSYNTHESIS IN *Strombidium* (CILIOPHORA, OLIGOTRICHIDA)

Diane K. Stoecker, Ann E. Michaels and Linda H. Davis

The chlorophyll content and photosynthetic rates of four marine planktonic oligotrichous ciliates in the genus *Strombidium* were determined in laboratory studies. *S. capitatum* had an average chlorophyall *a* content of 49 pg $cell^{-1}$ and a maximum photosynthetic rate ($P_{max}$) of 80 pg C $cell^{-1}$ $h^{-1}$); *S. conicum* had an average chlorophyll content of 14 pg $cell^{-1}$ and a $P_{max}$ of 44 pg C $cell^{-1}h^{-1}$; *S. acutum* had an average chlorophyll content of 50 pg $cell^{-1}$ and a $P_{max}$ of 37 pg C $cell^{-1}h^{-1}$; an undescribed *Strombidium* species (Strain SPCH) had an average chlorophyll content of 100 pg $cell^{-1}$ and a $P_{max}$ of 98 pg C $cell^{-1}h^{-1}$. The estimated percent of body carbon fixed $h^{-1}$ ranged from 1.5% in *S. capitatum* to 9.2% in "SPCH". Chloroplast-retaining *Strombidium* spp. vary in their photosynthetic capacity; some species are more autotrophic than others.

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WHOI Contribution No. 6567.

## CHLOROPLAST RETENTION BY MARINE PLANKTONIC CILIATES

Diane K. Stoecker and Mary W. Silver

Many marine planktonic ciliates in the family Strombidiidae, order Oligotrichida, are pigmented because they sequester algal chloroplasts. When epifluorescence microscopy is used, the pigmented bodies fluoresce red or orange, indicating the presence of chlorophyll *a* and p]hycoerythrin, respectively. In transmission electron micrographs, it is evident that these pigmented bodies are intact chloroplasts.

Chloroplast retention in ciliates had not been previously investigated experimentally. However, because the chloroplasts appear to be in good condition, they were thought to be photosynthetically functional. We have isolated several pigmented ciliates, including *Laboea* sp. and several *Strombidium* spp., from coastal waters and have grown them in culture on a mixture of microalgae on a 14-hour L:10-hour D light cycle. Using cultured material, we are investigating (1) the specificity of chloroplast retention; (2) the life span of se-

questered chloroplasts; (3) the growth of ciliates in the light and dark, in the presence and absence of food; and (4) the chlorophyll content and rate of photosynthesis in the ciliates.

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WHOI Contribution No. 6562.

## OBLIGATE MIXOTROPHY IN Laboea strobila, A CILIATE WHICH RETAINS CHLOROPLASTS

Diane K. Stoecker, Mary W. Silver, Ann E. Michaels and Linda H. Davis

The planktonic ciliate, Laboea strobila Lohmann, sequesters photosynthetically functional chloroplasts derived from ingested algae. The chloroplasts lie free in the cytoplasm and are most abundant just under the pellicle of the ciliate. The maximum rate of photosynthesis ($P_{max}$) was 925 pg C ciliate$^{-1}$ h$^{-1}$ (3.7 pg C pg chl. a$^{-1}$h$^{-1}$). At saturating irradiance, the amount of carbon fixed h$^{-1}$ equaled 12.6% of the body carbon of the ciliate. To grow, L. strobila requires both light and algal food. In the absence of food, survival of L. strobila is significantly longer in the light than in the dark. Based on ingestion rate and photosynthetic rate, we calculate that photosynthesis can make an important contribution to this ciliate's carbon budget even when algal food is plentiful.

In press: Marine Biology.

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WHOI Contribution No. 6367.

## SWIMMING BEHAVIOR OF THE LARVAE OF Argopecten irradians LAMARCK IN RESPONSE TO THERMAL GRADIENTS

Rodman E. Taylor
and Judith McDowell Capuzzo

The response of bay scallop larvae, Argopecten irradians, to thermal gradients was investigated in order to see if specific behavioral mechanisms were elicited which might act to retain the larvae in embayments and estuaries. Five individual larval stages were observed in a water column during changes in temperature and salinity. The mean absolute velocity of larvae increased as size increased from trochophore stage (0.200 mm/s$^{-1}$) to the pediveliger stage (0.350 mm/s$^{-1}$). The most significant result of these experiments was the fact that when water temperature increases above ambient temperature, larvae descend to the bottom of the water column and when the water temperature decreases below ambient temperature, the larvae swim up into the water column, usually with great bursts of speed (up to 1.31 mm/s$^{-1}$). This response is virtually the same in all five larval stages. No measurable effects were observed for similar manipulations of salinity and light. Water temperature can change drastically during a tidal cycle in the shallow embayments of southern New England. These results show a possible mechanism for retention of bay scallop larvae in embayments and may help explain the disparity in population density between embayments.

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WHOI Contribution No. 6589.

## DEEP-WATER ZOOPLANKTON OF THE GUAYMAS BASIN HYDROTHERMAL VENT FIELD

Peter H. Wiebe, Nancy Copley, Cindy Van Dover, Armando Tamse F. Manrique

Zooplankton from the Guaymas Basin deep-sea vent field were collected with a 1-m$^2$ MOCNESS to examine the distribution of total standing stock, taxonomic composition, size frequency distribution of zooplankton, and the species composition of calanoid copepods. Low altitude (~100 m above the bottom) horizontal tows along and across the axis of the basin's southern trough, and oblique tows from the bottom of the basin (~2000 m) to the surface were made. Total biomass in near bottom samples (range: 13 to 46 cc/1000 m$^3$) was only about a factor of ten lower than in the upper 100 m. However, there was little or no evidence for enrichment of biomass in the ~100 m zone above the vent site relative to biomass at the same depth horizon over non-vent areas. Total numbers of individuals ranged between 2600 and 4800/1000 m$^3$. Calanoid copepods consistently ranked first in abundance of counts of the taxa, followed by cyclopoid copepods, ostracods, chaetognaths, and amphipods. Other less abundant taxa, but in some cases important contributors to total biomass, were coelenterates (siphonophores, medusae), decapod shrimp, and polychaetes.

Size-frequency analysis of individuals from each taxon indicated that the biomass and abundance spectra do not fit the theoretically expected spectra based on weight-dependent metabolism and growth. The pyra-

mid of biomass was substantially different from the pyramid of numbers in this deep-sea community.

Of the 67 species of copepods identified in two samples taken on low altitude tows, only 15 co-occurred in both samples. Many of the species in this relatively diverse community remain to be described. Larval and post-larval forms of benthic clams, gastropods, polychaetes, and crustaceans associated with the vents were collected 100-200 m above the southern trough indicating that post-larvae may play an active role in dispersal of hydrothermal vent species.

In press: Deep Sea Research.

Supported by: NSF Grants OCE83-11201 and OCE87-09962.

WHOI Contribution No. 6657.

## P O P U L A T I O N  E C O L O G Y

### APPROACHING SIZE AND AGE IN MATRIX POPULATION MODELS

Hal Caswell

Matrix projection models are one of the simplest and most powerful ways of investigating the evolutionary and demographic consequences of the life cycle. They are particularly well suited to organisms whose demographic properties are determined by size or developmental stage, rather than age. This paper addresses three issues involving the relation of size and age in these models: the choice of age or size as a state variable, the construction of size-classified models as approximations to models including both age and size, and the recovery of age-specific information from size-classified models.

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WHOI Contribution No. 6666.

### THEORY AND MODELS IN ECOLOGY: A DIFFERENT PERSPECTIVE

Hal Caswell

"Ecology is awash with all manner of untested (and often untestable) models, most claiming to be heuristic, many simply elaborations of earlier untested models. Entire journals are devoted to such work, and are as remote from biological reality as are faith-healers." (Simberloff 1981)

Many ecologists today regard ecological theory with suspicion, and the mathematical models which are its strongest tool as symptoms of a malignancy infecting the entire discipline. I believe this assessment to be fundamentally mistaken. It arises from a misunderstanding of theoretical problems, from the failure to recognize their status in ecology, and from misapprehension of the place of mathematical models in the solution of theoretical problems. In this note I propose a different perspective on theory and theorizing in ecology. To be as provocative as possible, I present my points as blatant assertions.

Before I assert, however, let me list some things I am not doing. As a Popperian falsificationist, I am not questioning the importance of the experimental testing of theories, although I will take exception to a philosophy that views such testing as the only worthwhile thing to do with a theory. Nor am I trying to protect ecological theory from criticism, although I will argue that certain critiques are mistaken. There is quite as much bad theoretical research in ecology as there is bad empirical research. But probably not more. Finally, I am not trying to set "theoreticians" against "empiricists". Quite the opposite; ecology will be better served by an improved understanding of the nature of theoretical research.

In press: Ecological Modelling.

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WHOI Contribution No. 6568.

### DENSITY DEPENDENCE IN CLONAL POPULATIONS: EXPERIMENTAL STUDIES WITH A MARINE BRYOZOAN (Membranipora membranacea L.)

C. Drew Harvell, Paul Simpson and Hal Caswell

The demography of Membranipora membranacea, a sub-annual, epiphytic bryozoan, was monitored in populations growing on fouling panels at low and high density. In natural populations, M. membranacea often forms monospecific, even-aged stands dominated by a single cohort. The bryozoan's demography is moderated by the effects of intraspecific crowding and predation by small, but extremely abundant nudibranchs. Colonies normally undergo a

sub-annual cycle of growth, stasis and reproduction, shrinkage and death. Crowding by conspecifics accelerates the transition to stasis, triggers early onset of reproduction, and results in increased stage-specific mortality. At the peak in colony size during August, the mean size among colonies grown at high population densities is 500 $mm^2$ and the mean size among colonies grown at low densities is 800 $mm^2$. Mortality was highly size dependent. Colonies on both low- and high-density panels lived an average of 12 weeks.

The demography of M. membranacea in the San Juan Archipelago is distinguished by: (1) pronounced seasonality, (2) uniform age (but not size) structure due to synchronous recruitment of the initial cohort, and (3) survival rates and fecundities that are influenced by population density and predators. The seasonal cycle of colony birth, growth, stasis, and senescence appears common among temperate colonies; also common may be the potential for living in steep density gradients and the consequences of intraspecific crowding for demography.

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WHOI Contribution No. 6414.

## PROJECTION MATRICES IN POPULATION BIOLOGY

Jan Van Groenendael, Hans de Kroon and Hal Caswell

Projection matrix models are widely used in population biology to project the present state of a population into the future, either as an attempt to forecast population dynamics, or as a way to evaluate life history hypotheses. Starting with the simplest discrete, linear time invariant case, we show how life cycle data can be structured into a projection matrix and how such a matrix is analysed. We discuss the biological interpretation of the limiting properties of such models, with special emphasis on perturbation analyses. The effects of relaxing the assumptions of linearity and of time-invariance are also discussed. Finally, we discuss the connection between projection matrix models and the secondary theorem of natural selection, which opens life cycle phenomena to evolutionary interpretation.

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WHOI Contribution No. 6676.

## CAN SIZE OF NATURAL POPULATIONS BE PREDICTED? A SUCCESSFUL MARINE EXAMPLE

James R. Weinberg

Simplicity of Leslie matrices makes them attractive models for use in forecasting, but there are reasons to believe they are too unrealistic for this application. Finite long-term population growth rates were computed from Leslie matrices, representing four cohorts of Gemma gemma in nature, to test whether these rates ever generated accurate forecasts of population size. G. gemma was chosen for investigation because its characteristics are appropriate for the population model in two ways: 1) little migration between populations, 2) survivorship and fecundity of all ages estimable with accuracy.

The long-term growth rates did generate accurate annual forecasts for this natural population of bivalves. In three of four years, forecasts of population size for 12 mo ahead were within 12-17% of those observed. At any single time the population was never even close to the theoretical stable age distribution (S.A.D.) associated with any numerically dominant cohort. Instead, the distribution oscillated like a wave, as predicted by theory. Furthermore, the average age distributions of the four distributions each year was not significantly different from the S.A.D., a result which was also predicted from demographic theory.

Supported by: WHOI.

WHOI Contribution No. 6560.

# Z O O P L A N K T O N

## VISUAL OBSERVATIONS OF PARTICLE MANIPULATION DURING FEEDING IN LARVAE OF A BIVALVE MOLLUSC

Scott M. Gallager

Suspension-feeding was observed and characterized in various larval stages of the bivalve Mercenaria mercenaria (Linne) using high speed video microscopy (60-240 images/s). Larvae were tethered in a micro flow-through chamber and exposed to varying prey type (Isochrysis aff. galbana, TISO and Synechococcus spp., SYN) and concentration ($10^2$ to $10^6$ cells/ml). Feeding appeared to consist of a series of distinct, independent steps: 1) capture of a cell by the pre- and post-oral cirri of the velum, 2) transport to the mouth by the food

groove, 3) concentration of cells into a bolus at the mouth, 4) selection or rejection of cells for entry into the esophagus and, 5) activation of a ciliated sphincter either to allow a cell to enter the stomach or to reject it from the esophagus. Probabilities of steps one and two appeared to be a function of the encounter rate of cells in the media as both prey types were captured and transported to the mouth with equal efficiency. Whereas, steps three, four and five were related to particle characteristics and the degree of gut satiation. Ingestion rate of Isochrysis cells was proportional to the encounter rate between concentrations of $10^2$ and $10^3$ cells/ml, but declined to an incipient level specific to larval size at cell centrations above $10^4$ cells/ml. The rate of cell rejection increased with increasing media concentration and was inversely proportional to ingestion rate above $10^3$ cells/ml. Filtration rates (i.e., volume swept clear based on number of cells transported to the mouth) remained high as cell concentration was increased (~16 and 90 µl/hr/larva for two and 10-day-old larvae, respectively), but precipitously fell as the highest concentration was approached. Conversely, clearance rates (i.e., volume swept clear based on number of cells ingested) generally declined with increasing cell concentration as has been reported for many other suspension-feeding organisms. When cells of Synechococcus and Isochrysis were offered at equal concentrations, the numerical ratio of cells ingested (SYN/TISO) declined from 48 to 3 in two and 10-day-old larvae, respectively; however, the volumetric ratio ranged from 0.24 to 0.03. This suggests that although larvae capture, transport and ingest cyanobacteria with equal efficiency compared with cells of Isochrysis, the biomass available from the larger cells far exceeds that of the smaller bacteria. Ten-day-old larvae with empty guts were exposed to a constant concentration of Isochrysis cells. Ingestion was high for the first six minutes (93 cells/min) and proportional to the rate of capture and transport to the mouth. This fell to 4.3 cells/min within nine minutes of initial exposure. A total of 635 cells were ingested before rejection exceeded ingestion rate. Observations suggest that current theories of feeding dynamics in bivalve larvae require re-evaluation to include the following: 1) mechanisms for decoupling locomotion and particle capture from ingestion and 2) both passive and active selection of prey.

In press: Bulletin of Marine Science.

Supported by: NOAA, Office of Sea Grant, Grant NA86A-D-SC090.

WHOI Contribution No. 6488.

## LARVAL FISHES AND ZOOPLANKTON IN A CYCLONIC EDDY IN HAWAIIAN WATERS

Phillip S. Lobel and Allan R. Robinson

A cold-core eddy occurred off the Kona coast of the island of Hawaii in July 1982. It remained in that area for about 70 days, sufficient time for many reef fish species to complete their planktonic larval phase. The deployment of eight current drogues in the eddy showed how entrainment of plankton from the reef and adjacent offshore waters can occur and that passive drift can return drifters from the deep sea to shore. Larval fishes may be swept past the island every 7 to 8 days in a weak eddy and 3.5 to 5 days in a strong eddy.

Plankton collections were made at night near the surface and at the same depth as the current drogues. Zooplankton were most concentrated at the eddy center. Taxonomic analysis of the plankton showed that the dominant animals were calanoid copepods, malacostracans, hyperiid amphipods, gastropod and bivalve larvae and chaetognaths. The densities of zooplankton and larval fishes in the eddy were higher than in the same area before the arrival of an eddy. Larval fishes were most abundant in the periphery and among these, midwater fish larvae (gonostomatids and myctophids) were the most numerous. Other numerous fish larvae in the eddy included scombrids, particularly Thunnus albacares, carangids and the reef fish, Abudefduf abdominalis (Pomacentridae).

The role of mesoscale eddies in the oceans is currently receiving a great deal of emphasis all around the world (Robinson, 1983). Eddies have been implicated as an important mechanism affecting the distribution and abundance of zooplankton and fishes (Wiebe et al., 1976, Boyd et al., 1978; Tranter et al., 1980, 1983a,b; Angel and Fasham, 1983; Brandt, 1983; Olson and Backus, 1985). Zooplankton and fishes entrained in an eddy can be transported across vast ocean distances by eddy advection (Wiebe et al., 1976; Wiebe, 1982; Backus and Craddock, 1982) or can be held in a limited domain by a stationary eddy (Lobel and Robinson, 1986). Zooplankton community composition within eddies can be quite distinct compared to those in adjacent waters (Wiebe et al., 1976; Wiebe and Flierl, 1983; Ortner et al., 1978). The consequences of these patterns to the life histories and evolution of zooplankton, micronekton and large pelagic animals are just now being elucidated.

In this paper, we continue the presentation of results from an investigation of a cyclonic eddy in Hawaiian waters during July-September 1982 (Lobel and Robinson 1986). This eddy remained essentially in one location for about 70 days

before moving along the archipelago. Our earlier paper described the physical oceanography of the eddy, followed its movement and examined the distribution of the various developmental stages of larval fishes in it. This paper examines the taxonomy of the larval fishes and their distribution, and enumerates the kinds of zooplankton. The densities of fishes and zooplankton are compared between the eddy and adjacent coastal waters and in the deep ocean before the eddy was present.

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WHOI Contribution No. 6424.

# DEPARTMENT OF CHEMISTRY
# FREDERICK L. SAYLES, CHAIRMAN

## INSTRUMENTS AND STATISTICS

### DETERMINATION OF $CCl_3F$ AND $CCl_2F_2$ IN SEAWATER AND AIR

John L. Bullister and R. F. Weiss

An improved analytical technique has been developed for the rapid and accurate shipboard measurement of two anthropogenically produced chlorofluorocarbons (CFCs), $CCl_3F$ (F-11) and $CCl_2F_2$ (F-12) in air and seawater. Gas samples (dry air or standard) are injected into a stream of purified gas and then concentrated in a low temperature trap. Seawater samples collected in oceanographic Niskin bottles are transferred into glass syringes for storage until analysis. An aliquot of approximately 30 $cm^3$ of seawater is introduced into a glass stripping chamber where the dissolved gases are purged with purified gas, and the evolved CFCs are concentrated in the same cold trap. The trap is subsequently isolated and heated and the CFCs are automatically transferred by a stream of carrier gas into a precolumn and then a chromatographic separating column. The $CCl_3F$ and $CCl_2F_2$ peaks are detected by an electron capture detector (ECD) and their areas are integrated digitally. CFC amounts are calculated using fitted calibration curves, generated by injection of various multiple aliquots of gas standard containing known concentrations of CFCs. Preliminary concentration values for these compounds are printed at the completion of each analysis. Total analysis time for air and water samples is less than 10 minutes, allowing detailed vertical profiles of the concentrations of these compounds in the water column and concentrations in the overlying atmosphere to be determined within a few hours of the completion of a hydrographic station. Typical relative standard deviations for analyses of $CCl_3F$ and $CCl_2F_2$ in replicate air samples are approximately 0.5%. Typical relative standard deviations for replicate analyses of dissolved $CCl_3F$ and $CCl_2F_2$ in near-surface seawater containing equilibrium levels of these compounds are approximately 1%. Limits of detection for both compounds in 30 $cm^3$ seawater samples are about $0.005 \times 10^{-12}$ mole per kilogram.

Supported by: NSF Grant OCE85-18372.

WHOI Contribution No. 6602.

## ORGANIC AND BIOLOGICAL CHEMISTRY

### SEASONAL VARIATION IN THE FLUX OF EUTHECOSOMATOUS PTEROPODS COLLECTED IN A DEEP SEDIMENT TRAP IN THE SARGASSO SEA

Ahuva Almogi-Labin, Christoph Hemleben and Werner G. Deuser

A four-year series of sediment trap samples from a depth of 3.2 km in the Sargasso Sea (32°05'N, 64°15'W) has revealed seasonal variations in the flux of euthecosomatous pteropods. Total pteropod flux is related to seasonal variations of the total-particulate and organic-carbon flux with a lag of 1-1.5 months. High flux of pteropods (>200 specimens $m^{-2}d^{-1}$) occurs in late winter to mid-summer. Shells of individual pteropod species arrive in deep water in a seasonal succession similar to that in the living assemblage. Peak fluxes of Styliola subula, Clio pyramidata and Limacina bulimoides were recorded from February to May. Limacina inflata, Limacina lesueuri and Cuvierina columnella entered the trap in maximum numbers from April to mid-August. Creseis virgula conica and C. acicula were most abundant from June to late-August. The latter two are non-migrating epipelagic pteropods and comprise less than 10% of the assemblage. Diel migrators dominate the pteropod assemblage (92%). During the summer months they appear to migrate at greater depth, without reaching surface water. Although many young are produced, only a small fraction, about 4% in the case of L. inflata and L. bulimoides, survives and reaches maturity. Adult shell size of L. inflata and L. bulimoides varies seasonally, reaching maximum size during spring, probably in response to increasing food availability.

In press: Deep-Sea Research.

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WHOI Contribution No. 6552.

### VARIATIONS IN NITROGEN ISOTOPIC COMPOSITION BETWEEN SINKING AND SUSPENDED PARTICLES: IMPLICATIONS FOR NITROGEN CYCLING AND PARTICLE TRANSFORMATION IN THE OPEN OCEAN

Mark A. Altabet

Significant and consistent differences in nitrogen isotopic ratio (measured as $\delta^{15}N$ relative to atmospheric $N_2$) are observed between suspended and sinking particles in the Sargasso Sea. Suspended particles in the euphotic zone have an annual average of $-0.2°/_{oo}$ while particles sinking out of the euphotic zone average $3.7°/_{oo}$. This latter value is equivalent to the average $\delta^{15}N$ value for the sources of new nitrogen and appears to be similar to the $\delta^{15}N$ of $NO_3^-$ below the euphotic zone. The downward particle flux, in effect, preferentially exports $^{15}N$ out of the euphotic zone, causing suspended particles to be depleted in $^{15}N$ relative to the new nitrogen sources. Feeding by macrozooplankton on suspended particles that are one or two trophic levels removed from phytoplankton and therefore enriched by $^{15}N$ may account for the observations. Suspended particles below the base of the euphotic zone are $7°/_{oo}$ higher in $\delta^{15}N$ relative to those within in the euphotic zone reflecting, in part, their transport there as large particles. Since suspended particles below the euphotic zone are also higher in $\delta^{15}N$ relative to sinking particles by $3°/_{oo}$, isotopic fractionation must occur during the disaggregation of sinking particles and/or the subsequent degradation of suspended particles.

In press: Deep-Sea Research.

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WHOI Contribution No. 6565.

## BOMB RADIOCARBON IN METABOLICALLY INERT TISSUES FROM TERRESTRIAL AND MARINE MAMMALS

Jeffrey L. Bada, Christian D. Vrolijk, Stephen Brown, Ellen R. M. Druffel and Robert E. M. Hedges

The detonation of thermonuclear weapons in the atmosphere during the 1950s and early 1960s nearly doubled the radiocarbon ($^{14}C$) activity of tropospheric carbon dioxide by 1964. Although this bomb radiocarbon signal has steadily decreased since the ratification of the limited atmospheric test ban treaty in October 1963, the current radiocarbon activity of atmospheric carbon still exceeds pre-bomb levels by about 15-20%. The radiocarbon levels of dissolved inorganic carbon (DIC) in ocean surface waters also increased, but more slowly and to a much smaller extent. Mixing with subsurface waters acted to dampen the bomb radiocarbon signal in surface waters, and the long residence time of radiocarbon in the atmosphere delayed the peak maximum in the ocean nearly 10 years. Numerous studies have utilized the radiocarbon "spike" derived from nuclear weapons testing to investigate various oceanographic, geochemical, and biological processes. We report here measurements on monkey eye lens nucleus proteins and a narwhal tusk, biological tissues which have sampled the bomb radiocarbon signal in different ways. The results confirm the metabolic inertness of eye lens nucleus proteins and demonstrate the feasibility of measuring radiocarbon in small samples of biological tissue using accelerator mass spectrometry (AMS). The narwhal tusk provides a unique record of the radiocarbon activity in Arctic Ocean waters over most of the 20th century.

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WHOI Contribution No. 6505.

## CHEMICALLY MEDIATED FLUORESCENCE YIELD SWITCHING IN NITROXIDE-FLUOROPHORE ADDUCTS: OPTICAL SENSORS OF RADICAL/ REDOX REACTIONS

Neil V. Blough and Daniel J. Simpson

The absorption and fluorescence emission spectra and quantum yields of a series of paramagnetic nitroxide-napthalene adducts are compared to those of diamagnetic analogues. While the absorption and emission energies of these compounds are unaffected by the presence of the nitroxide radical substituent(s), the fluorescence quantum yields of the paramagnetic derivatives are 2.9 to 60-fold lower than the corresponding diamagnetic derivatives. Additionally, chemical reduction of the nitroxide moiety to a diamagnetic hydroxylamine produces a fluorescence yield increase that parallels nitroxyl radical loss. On the basis of this chemically mediated optical switching, compounds of this class may prove to be broadly applicable as sensitive optical probes for radicals and redox-active species in biological and chemical systems.

In press: Journal of the American Chemical Society.

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WHOI Contribution No. 6532

## TEMPORAL VARIATIONS OF PARTICLE FLUXES IN THE DEEP SUBTROPICAL AND TROPICAL NORTH ATLANTIC: EULERIAN VERSUS LAGRANGIAN EFFECTS

Werner G. Deuser, Frank E. Muller-Karger, and Christoph Hemleben

The flux of particles measured by sediment traps in the deep water of the Sargasso Sea and western tropical North Atlantic undergoes pronounced temporal variation. In the Sargasso Sea the variability is largely due to seasonal changes in mixed-layer depth and attendant changes in primary productivity affecting a wide region. By contrast, the variability in the tropical Atlantic appears to be caused by patches of elevated nutrient and pigment concentrations which have their origin in the plumes of the Amazon and Orinoco Rivers. Coastal Zone Color Scanner scenes demonstrate the great seasonal and interannual differences in the direction and dispersal patterns of the plumes. The river plumes break up into irregular which may pass through the catchment area of a sediment trap at varying rates, thereby creating the impression of almost random temporal flux variability at a fixed trap site.

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WHOI Contribution No. 6683.

## BIOACCUMULATION OF HYDROPHOBIC ORGANIC POLLUTANT COMPOUNDS

John W. Farrington

The purpose of this chapter is to provide a brief overview of the biogeochemistry of organic chemicals of environmental concern in aquatic ecosystems and the key aspects important to uptake, retention, release, and metabolism by aquatic organisms. The literature is not exhaustively reviewed, but key review articles or books are cited within the overview context, and a few illustrative examples are discussed in more detail. An integrative mathematical modelling approach to this topic is discussed by O'Connor in Chapter 13 of this book.

Organic chemicals of environmental concern are those with known or potentially deleterious effects on natural resource populations and on humans. Rather than use more cumbersome terminology, I shall refer to these compounds as pollutant organic chemicals. I do so with the explicit recognition that many of the chemicals have not been proven to have deleterious effects except in a limited number of circumstances, and many organic chemicals have never been tested for deleterious effects but are suspect because of a chemical structure similar to compounds proven to have deleterious effects.

In press: Ecotoxicology, S. Levin, M. Harwell, K. Kimball (eds.), Springer-Verlag.

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WHOI Contribution No. 6437.

## REVIEW OF MARINE ORGANIC GEOCHEMISTRY

John W. Farrington

Publication of this review will occur within a few months of the tenth anniversary of the volume, Concepts in marine Organic Chemistry (Anderson, 1977). That volume reviewed the topic up to that time and provided a prognosis and stimulus for a strong program of research in marine organic geochemistry for the past ten years. The previous United States report to IUGG on this topic (Gagosian, 1983) provided an excellent review of the literature of 1979-1982 and focused in an informative manner on several specific subtopics. This review adopts the same organization format, although some of the subtopics are new and some previous subtopics are not emphasized because of the marine organic geochemical research and the new divisions within the United States report on Chemical Oceanography and Paleo-oceanography.

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WHOI Contribution No. 6412.

## SUPERCRITICAL FLUID CHROMATOGRAPHY-MASS SPECTROMETRY OF CAROTENOID PIGMENTS

Nelson M. Frew, Carl G. Johnson and Richard H. Bromund

Combined supercritical fluid chromatography-mass spectrometry is shown to be a useful new tool for the separation and identification of carotenoids, relatively involatile, labile pigments which contain

multiple functional groups spanning a range of polarities. The most promising stationary phases for capillary SFC of complex natural mixtures of carotenoids are the cyanopropylpolysiloxanes and polyethylene glycols. The extremely mild ionization conditions which prevail using supercritical $CO_2$ as the mobile phase, produce superior quality mass spectra for fragile carotenoids such as fucoxanthin and its derivatives, as compared with earlier in-beam desorption CI techniques. The CI-$CH_4$ fragmentation of many other carotenoids under these conditions is minimal; the simplicity of their spectra may be advantageous in determining trace level distributions using molecular ion abundances.

In press: Supercritical Fluid Extraction and Chromatography--Techniques and Applications, B. Carpentier and M. Sevenants, eds., ACS Symposium Series.

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WHOI Contribution No. 6510.

## PETROLOGY AND MORPHOLOGY OF THE VOLCANICS FROM THE EAST PACIFIC RISE NEAR 12°43'N AND 11°30'N

Roger Hekinian, Geoffrey Thompson and Daniel Bideau

Volcanics collected from the axial graben and off-axis volcanoes (<20 km from the rise axis) on the East Pacific Rise near 12°43'N and 11°30'N consist of a variety of basaltic flows. They are divided into four main groups: 1) Depleted olivine basalts enriched in Mg-olivine, with a high Mg# (>66-70), a low K/Ti (<0.11) ratio, low Nb (<5 ppm) and low Zr (<100 ppm) contents. 2) More evolved plagioclase-olivine-(pyroxene) basalts with a Mg# of 58-66, K/Ti ratio of 0.11-0.25, and variable Nb and Zr contents. 3) Enriched (Ti-K) basalts with variable Mg# (58-67), a high K/Ti (.29-.46) ratio, high Nb (>10 ppm) and high Zr (130-150 ppm) contents. 4) Plagioclase rich basalts having the composition of the least evolved and depleted olivine basalts, but enriched in early formed plagioclase set in a glassy matrix.

The morphology of the different lava flows encountered in the various geological settings is comparable, and does not show any definite correlation with the composition of the volcanics. There are no substantial differences between flows erupted on off-axis seamounts and those from the axial graben, except for the prominent occurrence of hyaloclastites in the samples recovered from off-axis seamounts.

From detailed investigations correlating geological settings and the composition of the eruptives, it is inferred that the zones of magmatic upwelling are restricted to well individualized structures such as portions of the axial grabens (<1 km. in width) and off-axis volcanoes. The marked diversities of the volcanics erupted are probably due to two main parental sources, one of which gave rise to the depleted olivine basalt and the other one to the enriched Ti-K basalts. Both of these parental sources reflect the heterogeneity of the mantle which supplies melt to shallow level magma chambers located underneath the axial grabens and the off-axis seamounts near 12°43'N and 11°30'N on the EPR. It is also inferred that the different basaltic suites are the result of cyclic eruptive events. This cyclicity is related to the replenishment of shallow magmatic reservoirs where crystal fractionation and magmatic mixing between depleted (olivine basalts) and undepleted melts (Ti-K basalt) has taken place.

Supported by: NSF Grant OCE84-9977.

WHOI Contribution No. 6447.

## THE NITRATE FLUX INTO THE EUPHOTIC ZONE

William J. Jenkins

Throughout most of the year, there exists within the North Atlantic subtropical ocean mixed layer a $^3He$ excess which can only be attributed to a flux of tritiugenic $^3He$ from below. The upward flux required to support this excess can be computed as the convolution of the time series of $^3He$ excess and gas exchange rate. This flux is quantitatively consistent with the long-term evolution of the main thermocline inventories of tritium and $^3He$. Using the observed correlation of $^3He$ vs. nitrate within the upper main thermocline, I estimate the annually averaged upward flux of nitrate into the euphotic zone to be $0.6 \pm 0.2$ moles/$m^2$/y. This flux is adequate to support a new, non-regenerative primary productivity in excess of 3 moles carbon/$m^2$/y.

In press: Nature.

Supported by: NSF Grant OCE85-01171.

WHOI Contribution No. 6610.

## IDENTIFICATION OF ALIPHATIC KETO-CARBOXYLIC ACIDS IN MARINE AEROSOLS USING CAPILLARY GAS CHROMATOGRAPHY-MASS SPECTROMETRY

Kimitaka Kawamura and Robert B. Gagosian

Positional isomers of aliphatic keto-carboxylic acids ($C_6$-$C_{15}$) in marine aerosol samples collected in the North Pacific Ocean have been identified by using capillary gas chromatography-mass spectrometry (GC-MS). The keto group was determined to be in the γ- to (ω-1)-position. These ketoacids were isolated from aerosol filters by extraction with methanolic potassium hydroxide and derivatized to their corresponding methyl esters. The ketoacid methyl esters were purified by silica gel column chromatography prior to GC and GC-MS analysis. The results showed that 5-oxoundecanoic, 10-oxoundecanoic, 5-oxononanoic, 4-oxononanoic, 8-oxoundecanoic and 9-oxoundecanoic acids were dominant ketoacids in the marine aerosol samples studied. This paper presents the structural identification of the positional isomers of aliphatic keto-acid methyl esters by electron impact mass spectrometry.

In press: Journal of Chromatography.

Supported by: NSF Grant OCE86-06666.

WHOI Contribution No. 6663.

## IDENTIFICATION OF ISOMERIC HYDROXY FATTY ACIDS IN AEROSOL SAMPLES BY CAPILLARY GAS CHROMATOGRAPHY-MASS SPECTROMETRY

Kimitaka Kawamura and Robert B. Gagosian

Isomeric mixtures of 5- to (ω-1)-monohydroxy fatty acids have been isolated from remote marine aerosols by methanolic potassium hydroxide extraction and silica gel column chromatography. Structures of the hydroxyacids were determined by comparison with high resolution gas chromatography-mass spectra (GC-MS) of authentic standards, employing methyl esters and methyl ester trimethylsilyl (TMS) derivatives. A series of monohydroxyacid positional isomers have been identified in the range $C_7$-$C_{15}$ with 5-hydroxyundecanoic and 10-hydroxyundecanoic acids as major isomers. Electron impact mass spectra of hydroxyacid methyl esters show characteristic α-cleavage ions (e.g., m/z 131 for 5-hydroxy homolog) and their methanol-eliminated ions (e.g., m/z 99). Mass spectra of the TMS derivatives also yield characteristic ions at m/z 133 + 14 m (m ≥5; m = position of carbon atom bearing OH group). These specific ions provide a useful tool in mass chromatography to detect individual positional isomers of hydroxy fatty acids in environmental samples.

In press: Journal of Chromatography.

Supported by: NSF Grant OCE86-06666.

WHOI Contribution No. 6665.

## BIOGEOCHEMISTRY OF BENZ(A)ANTHRACENE AT THE SEDIMENT-WATER INTERFACE

Anne E. McElroy, Bruce W. Tripp, John W. Farrington and John M. Teal

Two recirculating microcosms were used to study the fate of the polycyclic aromatic hydrocarbon (PAH) benz(a)anthracene (BA) near the sediment-water interface. In the absence of direct sunlight, degradation of $^{14}C$-labeled BA added to the water column was followed in the water column, in the sediment reservoir, and in the polychaete Nephtys incisa. Extensive metabolism of BA was observed in all components of the system.

In Press: Chemosphere.

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WHOI Contribution No. 6598.

## CAROTENOID DEHYDRATES IN RECENT MARINE SEDIMENTS

Daniel J. Repeta and Nelson M. Frew

A series of novel acetylenic carotenoid transformation products have been isolated from marine sediments and their structures confirmed by synthesis. These compounds arise from postdepositional metabolic dehydration of fucoxanthin, a major phytoplankton pigment.

Supported by: NSF Grant OCE83-10004.

WHOI Contribution No. 6541.

## FRACTIONATION OF STABLE CARBON ISOTOPES DURING CHEMOAUTOTROPHIC GROWTH OF SULFUR-OXIDIZING BACTERIA

Edward G. Ruby, Holger W. Jannasch, and Werner G. Deuser

Laboratory-grown strains of chemoautrotrophic Thiomicrospira sp. strain L-12 and Thiobacillus neapolitanus produced cell carbon that was 24.6 to 25.1 ppt (24.6 to 25.1 mg/g) lower in $^{13}C$ isotope abundance than the ambient source of carbon dioxide and bicarbonate. This degree of $^{13}C$ isotope depletion was comparable to that found in organic material produced in deep-sea hydrothermal-vent communities.

Published in: Applied and Environmental Microbiology, 53, 1940-1943, 1987.

WHOI Contribution No. 6405.

## INVESTIGATION ON THE EFFECTS OF ORGANIC SOLVENT EXTRACTION ON WHOLE-ROCK PYROLYSIS: MULTIPLE-LOBED AND SYMMETRICAL $P_2$ PEAKS

Martha E. Tarafa, Jean K. Whelan and John W. Farrington

Pyrolysis techniques provide an estimate of oil-generating potential of a sediment based on the amount of hydrocarbon of the $P_2$ (or $S_2$) peak. Multiple-lobed and symmetrical $P_2$ peaks were studied to determine if extractable bitumen affected the $P_2$ results. Samples from the Tiglukpuk and Ledbetter wells were analyzed using pyrolysis techniques as whole, unextracted, ground sediment and after organic solvent extraction. Results indicate that $P_2$ for the Tiglukpuk well appears unaffected by extractable bitumen. $P_2$ peaks for the Ledbetter well samples appear to be affected by extractable bitumen or by asphaltenes. Pyrolysis-gas chromatography (pyrolysis-GC) and pyrolysis-gas chromatography-mass spectrometry (pyrolysis-GC/MS) determined the composition of the portion of the $P_2$ peak for the Ledbetter well that was removed by organic solvent extraction. Pyrolysis-GC analysis also demonstrated that for the Ledbetter well gas generating organic material was not removed by organic solvents.

In press: Organic Geochemistry.

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WHOI Contribution No. 6486.

## MARINE AND TERRIGENOUS LIPIDS IN COASTAL SEDIMENTS FROM THE PERU UPWELLING REGION AT 15°S: STEROLS AND TRITERPENE ALCOHOLS

John K. Volkman, John W. Farrington, and Robert B. Gagosian

The distributions of free 4-desmethyl sterols in sediments from the peru coastal zone at 15°S have been determined. Major free sterols in the surface sediments include cholesterol, which is mainly derived from zooplankton, and two $C_{28}$ sterols: 24-methylcholesta-5,24(28)-dien-3ß-ol and 24-methylcholesta-5,22E-dien-3ß-ol both of which are derived from diatoms. Their concentrations decrease by almost an order of magnitude in the top 20 cm of sediment depth, indicating that free sterols are rapidly degraded in this sedimentary environment. Lipids from higher plants were also detected: long chain fatty acids and alcohols and various triterpenoid alcohols, including taraxerol, lupeol and α- and ß-amyrin. The concentrations are most terrigenous lipids varied by less than a factor of 3 over the same depth, and these changes were not correlated with changes in the concentrations of total organic carbon. Below 3 cm, lipids from higher plants predominated in the extractable lipid distributions due to the more rapid degradation of marine lipids. We postulate that there are significant marine sources of the higher plant sterols 24-ethylcholesterol, 24-ethylcholesta-5, 22E-dien-3ß-ol and 24-methylcholesterol in these sediments. A high proportion of many of the terrigenous lipids in these sediments are probably transported into the coastal zone by rivers, rather than from the atmosphere, and then redistributed by bottom currents.

In press: Organic Geochemistry.

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WHOI Contribution No. 6577.

## $C_1$-$C_8$ HYDROCARBONS IN SEDIMENTS FROM GUAYMAS BASIN, GULF OF CALIFORNIA - COMPARISON TO PERU MARGIN, JAPAN TRENCH AND CALIFORNIA BORDERLANDS

Jean K. Whelan, Bernd R. T. Simoneit and Martha E. Tarafa

Surface seafloor sediments, hydrothermal vent samples, and Deep Sea Drilling Project sediments (Hole 481A) from the Guaymas Basin were examined for $C_1$-$C_8$ hydrocarbons. The proportions of various classes of compounds were examined and compared to those from other geographic areas (Peru upwelling region and Japan Trench) to gain insight into the relative importance of thermal generation, migration and biodegradation.

Concentrations of $C_2$-$C_7$ hydrocarbons were about 10 to 10,000 times higher in geothermally warm (estimated to have been exposed to maximum temperatures in the range of 30 to 150°C) Guaymas Basin sediments in comparison to the low concentrations (0.1 to 10 ppb per compound) typical of geothermally cold (maximum thermal exposure less than 20°C) seafloor and DSDP diatomaceous sediments. However, one sediment sample from DSDP Site 477, estimated to have been exposed to temperatures of 300°C or higher in the past, showed only a limited hydrocarbon composition, consisting of $C_1$-$C_3$ alkanes and aromatic hydrocarbons only.

Alkene/alkane ratios of 0.1 or greater were typical of both geothermally cold sediments and also of very hydrocarbon-rich Alvin samples recovered from the seafloor. Because little or no alkene was generally detected in buried sediments exposed to geothermal temperatures greater than 30°C, it is suggested that the alkenes are produced by biogenic processes. Normal alkanes predominated over cyclic and branched structures in geothermally cooler (<20°C) sediments, with the proportion of cyclic and branched compounds increasing in hotter sediments. Concentrations of gem-dimethyl and aromatic compounds generally remained approximately constant or increased slightly with temperature in comparison with concentrations in geothermally cold shallow sediments. Similarities in compositions of branched and cyclic compounds were observed in some pairs of bitumen-rich Guaymas seafloor samples recovered from different areas, suggesting common mechanisms of light hydrocarbon generation and/or migration. Localized increases in ratios of specific cycloalkane ratios were observed adjacent to sill intrusions.

In press: Organic Geochemistry.

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WHOI Contribution No. 6582.

## THERMOGRAVIMETRIC FOURIER TRANSFORM INFRARED SPECTROSCOPY (TG-FTIR) OF PETROLEUM SOURCE ROCKS - INITIAL RESULTS

Jean K. Whelan, Peter R. Solomon, Girish V. Deshpande, and Robert M. Carangelo

The first results of thermogravimetric fourier transform infrared analysis (TG-FTIR), as applied to petroleum source rocks, are reported. Sample preparation and running time, roughly equivalent to those used for Rock Eval source rock pyrolysis analyses, are described. Initial results show that the TG-FTIR technique provides considerable additional geochemical information including:

a) Simultaneous $T_{max}$ values for thermal evolution of a number of constituents in addition to hydrocarbons and carbon dioxide - including methane, ethylene, carbon monoxide, ammonia, hydrogen cyanide, sulfur dioxide, and COS. $T_{max}$ values of several of these - including methane, ethylene, and ammonia - show progressive increases with maturation state. For one Alaskan North Slope well (Seabee), these $T_{max}$ values show an excellent correlation with vitrinite reflectance.

b) Data required for calculation of material balances of organic and inorganic sedimentary carbon, nitrogen, and sulfur.

c) Data for classification of sedimentary organic matter into kerogen Types I, II, and III (using either plots of organic H/C versus O/C or H/C versus organic carbon ratios) as well as according to depositional environment (using thermal evolution patterns of ammonia, HCN, $SO_2$ and COS and possibly $CO_2$).

In press: Energy and Fuels.

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WHOI Contribution No. 6590.

## RADIOCARBON IN DISSOLVED ORGANIC CARBON IN THE CENTRAL NORTH PACIFIC OCEAN

Peter M. Williams and Ellen R. M. Druffel

The origin of dissolved organic carbon (DOC) in the ocean has long been the subject of debate in the literature. Mantoura and Woodward have used the conservative nature of DOC in a British estuary to conclude that 50% or more of DOC in the oceans could be river-derived. Recent lignin results in the equatorial Pacific by Meyers-Schulte and Hedges, on the other hand, have indicated that a maximum of 10% of the DOC is potentially of terrestrial origin. In addition, the $\delta^{13}C$ signature of DOC ranges from -20 to -24°/₀₀ indicating that the primary source of DOC is from marine-derived organic carbon. In an effort to determine the major sources and cycling patterns of DOC in the oceanic water column, radiocarbon was measured in DOC and dissolved inorganic carbon (DIC) in a detailed depth profile in the oligotrophic gyre of the Central North Pacific. $\Delta^{14}C$ of DOC ranged

from -150°/₀₀ (1,310 yr BP) in surface waters to -540°/₀₀ (6,240 yr BP) at 5710 m, 40 m off the bottom. The surprising similarity in the shapes of the profiles of $\Delta^{14}C$ in the DOC and DIC pools suggests that similar processes are controlling the radiocarbon distribution in each of the two reservoirs. The depletion of the DOC-$\Delta^{14}C$ values by 300°/₀₀ with respect to the DIC-$\Delta^{14}C$ values suggests that a certain fraction or fractions of the DOC is recycled within the ocean on longer time scales than is DIC.

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WHOI Contribution No. 6593.

## NITRIC OXIDE AND NITROUS OXIDE PRODUCTION DURING DISSIMILATORY NITRITE REDUCTION BY P. PERFECTOMARINA

Oliver C. Zafiriou, Quentin S. Hanley and Gabriella Snyder

Cultures of Pseudomonas perfectomarina reduced nitrite in a chemically-defined marine medium, bubbled with nitrogen to remove dissolved gases with known, variable kinetics. $NO_{aq}$ and $N_2O_{aq}$ were removed in a flow-rate-dependent manner, with >50% of nitrite-N recoverable as NO, and ~75% as ($NO + N_2O$).

The flow-yield relationships fit a kinetic scheme in which cells produce extracellular $NO_{aq}$ and $N_2O_{aq}$; concurrently, these gases are consumed by competitive cellular processes and physical removal. The derived kinetic parameters give a limiting NO yield of 73 ± 8% and require concurrent uptake of $NO_{aq}$ and $N_2O_{aq}$.

These results demonstrate high yields and facile mobility of NO across the cell surface of P. perfectomarina in the presence of $NO_{aq}$ removal processes. As such processes may be common in nature, $NO_{aq}$ can be a major metastable product of denitrification.

The results also verify that $NO_{aq}$ is a major intermediate during balanced denitrification (no net NO flux at the cell surface), as has been proposed, provided that the $NO_{aq}$ production/uptake balance is not strongly dependent on net NO flux. This dependence and the nature of the "unscavengeable" pathway of reduced nitrite-N require elucidation.

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WHOI Contribution No. 6509.

# RADIOCHEMISTRY

## TRACERS OF CHEMICAL SCAVENGING IN THE OCEAN: BOUNDARY EFFECTS AND LARGE-SCALE CHEMICAL FRACTIONATION

Michael P. Bacon

Several nuclides in the natural radioactive decay series display a strong non-conservative behavior in the oceanic water column because of their removal to the sediments by uptake at the solid/solution interface. This removal process is commonly referred to as scavenging, and it is believed to be important in governing the behavior of many heavy metals and other trace substances in the ocean. Measurements of radioactive disequilibrium in seawater yield estimates of the rate at which scavenging occurs. Results show that removal times by scavenging are comparable to within-basin lateral mixing times. It follows that the distribution of the scavenged tracers should be sensitive to the spatial distribution of their sinks, and this has been demonstrated by observation, most notably in the case of $^{210}Pb$. The distribution of $^{210}Pb$ suggests a strong control by intensified uptake at boundaries, especially at the ocean margins. This conclusion has been confirmed by sediment traps and by measurements of $^{210}Pb$ accumulations in the sediment column. A similar phenomenon of intensified scavenging at ocean margins has been observed for $^{231}Pa$. Studies with $^{230}Th$, on the other hand, show that its delivery to the sediments is due mainly to the local flux of sinking particles. Thus two transport pathways for removal of scavenging are envisioned, one with a strong horizontal component due to the intensified uptake at the margins and the other with a strong vertical component due to the particle flux. Important large-scale chemical fractionations, best illustrated by comparative studies of $^{230}Th$ and $^{231}Pa$, are produced by differential partitioning of elements between these two pathways. Model calculations suggest that horizontal mixing rate and particle flux are important variables controlling the partitioning of reactive chemical substances between pelagic sediments of the interior ocean and hemipelagic sediments of the ocean margins. Changes in the extent of this partitioning through time may be recorded as changes in the $^{230}Th/^{231}Pa$ ratio through the sediment column.

In press: Phil. Trans. of Royal Society.

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WHOI Contribution No. 6643.

## CHERNOBYL RADIONUCLIDES IN A BLACK SEA SEDIMENT TRAP: A PRELIMINARY REPORT

Ken O. Buesseler, Hugh D. Livingston, Susumu Honjo, Bernward J. Hay, Steven J. Manganini, Egon T. Degens, Venu Ittekkot, and Tosun Konuk

Initial measurements of fallout Chernobyl radionuclides from a time series sediment trap in the southern Black Sea are presented. The sediment trap was deployed to collect settling particles over weekly intervals during three months after the Chernobyl event. A variety of gamma-emitting radionuclides from Chernobyl fallout were detected in a trap at 1071 m. The specific activities of $^{137}Cs$, $^{144}Ce$ and $^{106}Ru$ in the trap samples vary with time, and range from 0.5-2, 4-12 and 6-13 Bq/g, respectively. While there is a large maximum in the particle flux in July, the specific activities do not follow this trend. The relative activities of $^{137}Cs$, $^{144}Ce$ and $^{106}Ru$ appear to be reflecting their differing chemistries; the more soluble element Cs is much less rapidly scavenged than either of the more particle reactive elements, Ce and Ru. These results will form the basis for further studies using Chernobyl radionuclides as tracers of geochemical processes in the Black Sea.

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WHOI Contribution No. 6473.

## THE GEOCHEMISTRY OF FALLOUT PLUTONIUM IN THE NORTH ATLANTIC: I A PORE WATER STUDY IN SHELF, SLOPE AN DEEP-SEA SEDIMENTS

Ken O. Buesseler and Edward R. Sholkovitz

The distribution of fallout plutonium between pore waters and sediments in the Northwest Atlantic is examined in order to better define the potential for Pu migration from an within marine sediments.

Along a transect of seven cores collected between Woods Hole an Bermuda, the solid phase $^{239,240}Pu$, $^{210}Pb^{ex}$ and $^{137}Cs$ results do not suggest that any of these tracers are preferentially mobile within the cores. Pore water Pu activities appear to be controlled primarily by the distribution of Pu in the solid phase, with an operationally determine distribution coefficient, K, in the range of 0.2-23 x $10^4$. There is a trend in the Ks along the transect, with higher values in the $10^4$-$10^5$ range on the shelf an slope, to lower values $<10^4$ in the deep-sea cores. The exact mechanism for this shift has yet to be determined. While the Pu pore water activity at the seiment-water interface is elevated over near bottom water activities, the potential for Pu remobilization out of the sediments is small ($0.2\text{-}24 \times 10^{-5}$ pm $^{239,240}Pu/cm^2$ year). Sediment mixing models are not significantly altered by the inclusion of Pu diffusion terms, since the pore water terms are so small relative to typical sediment mixing rates.

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WHOI Contribution No. 6475.

## THE GEOCHEMISTRY OF FALLOUT PLUTONIUM IN THE NORTH ATLANTIC: II $^{240}PU/^{239}PU$ RATIOS AN THEIR SIGNIFICANCE

Ken O. Buesseler and Edward R. Sholkovitz

A systematic decrease in the $^{240}Pu/^{239}Pu$ ratio in marine sediments is found with increasing water depth along a transect of cores between Woods Hole and Bermuda. The $^{240}Pu/^{239}Pu$ atom ratios range from ≈0.18 on the shelf to ≈0.10 at 5000 m but do not change with depth in individual cores. A model is presented which can account for the range of $^{240}Pu/^{239}Pu$ ratios found in this and other similar studies (Noshkin and Gatrousis, 1974; Scott et al., 1983). We propose that there have been at least two distinct sources of fallout Pu to this region. The major source of Pu is global stratospheric fallout, characterized by a $^{240}Pu/^{239}Pu$ ratio of 0.18 and a relatively long residence time in seawater. The second source is characterized by a much lower $^{240}Pu/^{239}Pu$ ratio, and relative to global fallout it must have been much more efficiently removed from the water column to deep-sea sediments. We suggest that surface-based low yield testing at the Nevada Test Site is the only source of low ratio fallout Pu which could account for the timing, inven-

tories, and refractory characteristics of this second component of fallout Pu inputs to the North Atlantic.

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WHOI Contribution No. 6471.

## USING ANTHROPOGENIC TRITIUM AND $^3$HE TO STUDY SUBTROPICAL GYRE VENTILATION AND CIRCULATION

William J. Jenkins

Using tritium and $^3$He data from the Transient Tracers in the Ocean (TTO) expedition as well as two other contemporaneous cruises, we build a synoptic picture of the ventilation and circulation of the subtropical North Atlantic. We see clear evidence of gyre circulation in the tritium-$^3$He age distributions on the shallower isopycnals, permitting estimates of the rates of circulation averaged over timescales from months to decades. The entry points of fluid into the main thermocline and pathways of exchange with the upper ocean on seasonal to decade timescales appear clearly. It is the time-averaged transport processes on those timescales that are important to the uptake of carbon dioxide by the ocean. The overall relationship between tritium and $^3$He within the subtropics exhibits a systematic hook-like pattern which is consistent with "strong" ventilation of the gyre thermocline. That is, a fluid parcel entering the gyre thermocline makes only about one circuit around the gyre before being ventilated.

Finally, we present a timeseries of $^3$He measurements made over a two-year period near Bermuda. The mixed layer is demonstrably supersaturated in this isotope throughout a large part of the year, requiring a gas-exchange flux of this isotope to the atmosphere. Model results are presented which permit the calculation in the in situ solubility isotope ratio anomaly for helium (as affected by bubble injection and gas exchange), and which can be used to estimate the upward flux of this isotope. Since only a small fraction of this flux can be produced in the mixed layer, this helium must be "mined" from the main thermocline. The computed flux is consistent with the long-term evolution of the inventories of tritium and $^3$He within the main thermocline. This flux has implications regarding the vertical transport of material within and from the permanent thermocline. A single observation of what may be one of the processes responsible for this upward flux is discussed.

In Press: Phil. Trans. Roy. Soc. (London).

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WHOI Contribution No. 6609.

## INTERPRETATION OF $^{239,240}$PU IN THE ATLANTIC SEDIMENTS WITH A NON-STEADY STATE INPUT MODEL

Georges Lapicque, Hugh D. Livingston, Claude E. Lambert, Edouard Bard and Laurent D. Lebeyrie

We present a rapid interpretation technique of the input function of $^{239,240}$Pu in North Atlantic slope and abyssal oxic sediments, based upon a diffusion model fed with two different modes of input, pulse and step functions. This method is applied to a unique instantaneous source: the main fallout peak. The eventual presence of an additional step-like input is also considered. The apparent diffusivity coefficient lies in the range $10^{-8}$ to $10^{-7}$cm$^{-2}$ s$^{-1}$ for cores of 200 to 4,000 m water depth.

In press: Deep-Sea Research.

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WHOI Contribution No. 6452.

## THE USE OF CS AND SR ISOTOPES AS TRACERS IN THE ARCTIC MEDITERRANEAN SEAS

Hugh D. Livingston

The Arctic Mediterranean seas constitute an oceanic region in which the thermohaline circulation has a strong advective component and deep ventilation processes are very active relative to other oceanic areas. Details of the nature of these circulation processes have been revealed through use of Cs and Sr isotopes from bomb fallout and nuclear waste sources as ocean tracers. In both cases their regional input is dominated by advective supply in the Norwegian Atlantic Current and Norwegian Coastal Current, respectively. The

different temporal, spatial, and compositional input patterns of these tracers have been used to study different facets of the regional circulation. These input differences and some representative applications of the use of these tracers are reviewed. The data discussed derive from samples collected both from research vessels and from Arctic ice-camps. The topics addressed include:

a) the role of Arctic Intermediate Water as source, supplying recent surface water in North Atlantic Deep Water via the Denmark Strait overflow;

b) deep convective mixing in the Greenland Sea;

c) circulation or recirculation of Atlantic water in the Arctic basins; and

d) the role of Arctic shelfwaters in the ventilation of intermediate and deep water in the Eurasian and Canadian basins.

In press: Philosophical Transactions of the Royal Society, London.

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WHOI Contribution No. 6478.

## NITRIC OXIDE FLUXES IN OCEANIC OXYGEN GRADIENTS

Oliver C. Zafiriou

We report finding nitric oxide ($(NO)_{aq}$ = 0-0.4 nM) in seawater with ($O_2$) < 100 μM. On-deck incubations on one cruise imply a flux of ~13% of the ammonia oxidation flux, indicating a biogeochemically significant process. Laboratory experiments show substantial (4-70%) yields of NO from nitrifying and denitrifying bacteria, including marine species and from chemical processes. The environmental sources and sinks of NO remain unidentified. Figure 1 shows the conventional marine nitrogen cycle and some possible pathways involving $NO_{aq}$. The availability of NO-N and its products for biological assimilation is unknown. Our findings raise the significant possibility that extracellular NO may be a new, chemically and environmentally novel mechanism "denitrifying" fixed N. The major sink for fixed nitrogen is anaerobic or microaerobic denitrification to $N_2$.

Supported by: NSF Grant OCE86-01618.

WHOI Contribution No. 6463.

# SEAWATER AND GEOCHEMISTRY

## EPR MEASUREMENTS OF PHOTOCHEMICAL RADICAL PRODUCTION IN HUMIC SUBSTANCES: I. EFFECTS OF $O_2$ AND CHARGE ON RADICAL SCAVENGING BY NITROXIDES

Neil V. Blough

Electron paramagnetic resonance spectroscopy (EPR) was employed to measure the ability of Aldrich humic acid (HA) to photosensitize the consumption of a series of cationic, neutral and anionic nitroxides. These stable organic radicals react rapidly with a suite of inorganic and organic radicals to form diamagnetic products. In the presence of 250 μg/ml HA and under near-natural light conditions, easily detectable rates of nitroxide consumption are observed in both air and Ar equilibrated samples. However, at a given nitroxide concentration, significantly lower rates of nitroxide loss are observed in the presence of air, consistent with the view that $O_2$ and nitroxides compete for a substantial portion of the total radical pool. The initial rates of loss decrease in the order cationic > neutral >> anionic indicting that there is an electrostatic effect on the rate constants for scavenging. These findings suggest that negative charge on the humic influences the efficiency with which nitroxides can react with radicals on the humic structure. The use of EPR to detect radical scavenging by nitroxides represents a sensitive means for estimating free radical photoinitiation rates in mixtures of chemically ill-defined organic material such as HA.

In press: Environmental Science and Technology.

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WHOI Contribution No. 6401.

## HIGH PRECISION MEASUREMENTS OF ALKALINITY AND TOTAL CARBON DIOXIDE IN SEAWATER BY POTENTIOMETRIC TITRATION: 1. PRESENCE OF UNKNOWN PROTOLYTE(S)?

Alvin L. Bradshaw and Peter G. Brewer

An automated system for measuring alkalinity and total carbon dioxide in seawater by potentiomentric titration is described. Single observation standard errors of ~1 μequiv./kg and ~2 μmole/kg for alkalinity and total carbon dioxide are obtained using this system. The titration total carbon dioxide results are about 21 μmole/kg higher than those obtained by gas extraction methods which, unlike the titration method, do not require detailed knowledge of the chemistry of the seawater samples. Possible explanations of these differences include: an error in the physico-chemical model; a persistent contamination problem; or the presence of an unknown protolyte (HX) in natural sea water. We find this latter hypothesis most intriguing. We show that a species with a pK between 6.0 (carbonic acid) and 8.7 (boric acid) would not affect the alkalinity, but would be recorded putatively as "total $CO_2$" in a titration procedure, and suggest that such a species may occur at significant concentration in sea water.

In press: Marine Chemistry.

Supported by: NSF Grant OCE83-16709.

WHOI Contribution No. 6492.

## HIGH PRECISION MEASUREMENTS OF ALKALINITY AND TOTAL CARBON DIOXIDE IN SEAWATER BY POTENTIOMETRIC TITRATION: 2. MEASUREMENTS ON STANDARD SOLUTIONS

Alvin L. Bradshaw and Peter G. Brewer

We have prepared standard solutions identical to those of Hansson (1973) for the validation of titration procedures used to determine the alkalinity and total carbon dioxide content of sea water. We show that both titrimetric and gas extraction (coulometry) procedures yield virtually identical results of 2140.5±2.7 μm $CO_2$/kg for such solutions. In earlier work we had reported that measurements on natural sea waters yielded discrepancies of 21 μm $CO_2$/kg, which we tentatively ascribed to the presence of unknown organic acids masquerading as $CO_2$ in the titration scheme, and generally unrecognized in thermodynamic models of the proton condition of sea water. The results presented here tend to confirm this hypothesis.

Supported by: NSF Grant OCE20-1461.

WHOI Contribution No. 6495.

## OCEAN CHEMICAL FLUXES 1983-1986

Peter G. Brewer and David M. Glover

This review covers U.S. contributions in marine chemistry 1983-1986 in the areas of nutrient chemistry, carbon cycle, trace elements, oxygen cycling, radioisotopes (natural and artificial), particles and primary productivity. In most cases a simple review of important trends in this very large and diverse literature set is all that can be considered. The literature explosion in these areas results in more than 350 references.

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WHOI Contribution No. 6435.

## HYDROXIDE DECOMPOSITION OF DIMETHYLSULFONIOPROPIONATE TO FORM DIMETHYLSULFIDE

John W. H. Dacey and Neil V. Blough

The kinetics of DMS production resulting from reaction of $OH^-$ with DMSP were investigated as a function of hydroxide concentration and temperature. The reaction was first-order with respect to DMSP and $OH^-$. The second order rate constant at 20 ±1°C is 0.0044 $M^{-1}$ $sec^{-1}$. The activation energy for this reaction is 14.4 kcal $mole^{-1}$. Our investigation indicates that the rate of reaction of DMSP with $OH^-$ is very slow at the pH of seawater (half-life of about 8 years at 10°C), suggesting that DMSP, which may be a major precursor of DMS in seawater, decomposes in the ocean by other mechanisms. We have cultured a bacterium which produced DMS from DMSP quantitatively at rates many orders of magnitude higher than indicated by $OH^{-1}$ decomposition, suggesting that enzymatic processes accelerate the production of DMS from DMSP in seawater.

In press: Geophysical Research Letters.

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WHOI Contribution No. 6566.

## VARIABILITY OF HYDROGRAPHY AND PARTICLE FLUX: TRANSIENT AND LONG-TERM RELATIONSHIPS

W. G. Deuser

Particle flux measurements in the deep Sargasso Sea over a period of more than eight years are compared with contemporaneous hydrographic data from nearby Station 'S'. The comparison suggests that, con-

trary to expectations, three periods of unusually high particle flux were not associated with the passage of cold-core rings, which are known to have higher productivity and biomass than Sargasso Sea water. Rather, the high-flux periods appear to have been associated with the presence of warmer-than-usual water in the upper half kilometer of the water column. It is surmised that the warm water is diagnostic of some oceanographic feature which injects nutrients into the euphotic zone, but the mechanism by which this happens is unclear.

Comparison of average annual cycles of mixed-layer depth and particle flux over the eight years shows that flux lags behind mixed-layer depth by 1.5 months and that the two are highly correlated if the three periods of unusually high flux are removed. The annual flux cycle lags behind the cycles of length of daylight and sea surface temperature by three months and one month, respectively.

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WHOI Contribution No. 6419.

## GOLD AND NATIVE COPPER IN SUPERGENE SULPHIDES FROM THE MID-ATLANTIC RIDGE

Mark D. Hannington, Geoffrey Thompson, Peter A. Rona and Steve D. Scott

In 1985, black smokers and massive sulphide deposits were discovered in the TAG hydrothermal field, in the rift valley of the Mid-Atlantic Ridge near latitude 26°08'N. Sulphide samples from chimneys and mounds were recovered by dredging at a depth of 3700 m. Mineralogical and chemical analyses of the samples reveals (1) primary, unaltered Zn-Fe-Cu-sulphides containing 1 to 4 ppm Au (0.03 to 0.12 oz/ton) and (2) secondary Cu-rich sulphides with native copper, formed by supergene alteration of primary Cu-Fe-sulphides, containing up to 16.4 ppm Au (0.48 oz/ton) as free native gold. This is the first reported occurrence of secondary enrichment of gold and copper in recent submarine sulphides. The high gold grades and native copper associated with secondary Cu-sulphides resemble occurrences in some supergene gossans overlying ancient massive sulphide deposits on land.

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WHOI Contribution No. 6672.

## ALONG-AXIS VARIATIONS IN SEAFLOOR SPREADING IN THE MARK AREA

Jeffrey A. Karson, Geoffrey Thompson, Susan E. Humphris, John M. Edmond, Wilfred B. Bryan, J. R. Brown, A. T. Winters, R. A. Pockalny, J. F. Casey, A. C. Campbell, Gary Klinkhammer, M. R. Palmer, R. J. Kinzler and Margaret M. Sulanowska

Recent investigations with the manned submersible Alvin and the Angus deep-towed camera sled greatly extended the known range of variations in the style of seafloor spreading along the axis of the Mid-Atlantic Ridge. Five transects of the spreading centre at intervals of 10-20 km south of the Kane Fracture Zone at 24°N latitude demonstrate dramatic changes in the style and magnitude of tectonic extension, development of the neovolcanic zone, expression of hydrothermal venting, types of lithologic exposures and morphology of the median valley.

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WHOI Contribution No. 6678.

## LONG-CHAIN DICARBOXYLIC ACIDS AS INDICATORS OF ATMOSPHERIC TRANSPORT OF SOIL ORGANIC MATTER

Kimitaka Kawamura and Robert B. Gagosian

The distributions of lipids, such as n-alkanes, fatty alcohols and fatty acids in remote marine aerosols, have recently been used to ascertain the importance of atmospheric transport of continentally derived organic matter to open-ocean environments (1-6). However, these compound classes cannot be used to differentiate between a direct contribution from plant emissions or contributions from soil organic matter due to the similar compound distribution patterns of these two sources. Here we report the discovery of a homologous series of α,ω-dicarboxylic acids ($C_5$-$C_{32}$) in aerosol samples collected from the remote North Pacific. The distributions (>$C_{12}$) of this series are characterized by a predominance of $C_{20}$-$C_{32}$ compounds with a minor peak at $C_{16}$. This pattern is consistent with the diacid distributions found in soils, whereas plant leaf diacid distributions are dominated by the $C_{16}$ diacid. The high concentrations of these long-chain diacids found in aerosols correlated with the transport of material originating from

Alaska and Siberia as determined by long-range meteorological trajectory analysis. Hence, long-chain dicarboxylic acids can be useful as tracers for the atmospheric transport of soil organic material.

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WHOI Contribution No. 6504.

## TEMPORAL HELIUM ISOTOPIC VARIATIONS WITHIN HAWAIIAN VOLCANOES: BASALTS FROM MAUNA LOA AND HALEAKALA

Mark D. Kurz, Michael O. Garcia, Fred A. Frey, and Peggy A. O'Brien

Helium isotope ratios measured in basalts spanning the subaerial eruptive history of Mauna Loa and Haleakala vary systematically with eruption age. In both volcanoes, olivine mineral separates from the oldest samples have the highest $^3He/^4He$ ratios. The Haleakala samples studied range in age from older than one million years to historic time, while the Mauna Loa samples are radiocarbon dated flows younger than 30,000 years old. The Honomanu tholeiites are the oldest samples from Haleakala and have $^3He/^4He$ ratios that range from 13 to 16.8 x atmospheric, while the younger Kula and Hana series alkali basalts all have $^3He/^4He$ close to 8 x atmospheric. A similar range is observed on Mauna Loa; the oldest samples (roughly 30,000 years) have $^3He/^4He$ ratios of 15 to 20 x atmospheric, with a relatively smooth decrease to 8 x atmospheric with decreasing age. The consistent trend of decreasing $^3He/^4He$ ratio with time in both volcanoes, coherence between the helium with Sr and Nd isotopes (for Haleakala), and the similarity of $^3He/^4He$ in the late stage basalts to normal mid-ocean ridge basalt (MORB) helium, argue against the decrease being the result of radiogenic ingrowth of $^4He$. The data strongly suggest an undegassed (i.e having high $^3He/(Th+U)$) mantle source for the early shield building stages of Hawaiian volcanism, and are consistent with the hotspot/mantle plume model. The data are difficult to reconcile with models for Hawaiian volcanism that require recycled oceanic crust or derivation from a MORB related upper mantle source. We interpret the decrease in $^3He/^4He$ with volcano evolution to result from an increasing involvement of normal (i.e., depleted) mantle and/or lithosphere during the late stages of Hawaiian volcanism.

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## HELIUM ISOTOPIC VARIABILITY WITHIN SINGLE DIAMONDS FROM THE ORAPA KIMBERLITE PIPE

Mark D. Kurz, John J. Gurney, William J. Jenkins, and Dempsey E. Lott

The distribution and isotopic composition of helium has been measured in a suite of well-characterized one carat diamonds from the Orapa kimberlite, Botswana. Crushing of the diamonds in vacuo indicates that most of the helium is contained by the matrix (generally greater than 90%), rather than by the inclusions. Step heating experiments, performed on inclusion-free fragments remaining after crushing, indicate that the $^3He/^4He$ ratio is variable within individual diamonds. The fragments, as small as 10 milligrams, were heated in two timed steps, both at 2000°C. In every case, lower $^3He/^4He$ ratios are observed in the first graphitization step (.05 to 3 x atmospheric), while the last heating step releases helium with systematically higher $^3He/^4He$ ratio (30 to 80 x atmospheric). We suggest that this internal isotopic variability is the result of stepwise graphitization: the first heating step initiates graphitization, which nucleates around defects, and the second heating step graphitizes the relatively defect free regions of the diamond. The $^3He/^4He$ ratio measured, using the partial graphitization technique, differs by up to a factor of 100 within a single specimen. The inclusion-free fragments release small quantities of helium below 2000°C, which suggests that helium release is obtained only by graphitization. The $^3He$ contents of the monocrystalline diamonds are relatively constant (at ~3 x $10^{-13}$ ccSTP/gram) and indicate that most of the isotopic variability is due to radiogenic $^4He$. The variations in $^4He$ content are either related to zoning of Th and U in the diamonds (i.e., in situ decay), to zoning of inherited $^4He$, or to implantation of $\alpha$-particles from a Th and U rich environment (i.e., kimberlite). Because the Orapa diamonds were mined from at least 40 meters depth in the kimberlite, spallation reactions from cosmic ray interactions is not a significant source of $^3He$. However, calculations based on the age of the kimberlite (90 m.y.) and reasonable Th and U abundances suggest that most of the $^3He$ in the Orapa diamonds could be produced by $^6Li(n,\alpha)T$ in the diamond. Although this may not be true of all dia-

monds, nuclear reactions in the crust and mantle (including spallation reactions at the surface) can explain many of the high $^3He/^4He$ ratios previously reported for diamonds.

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WHOI Contribution No. 6490.

## RADIOCARBON RECORD IN NAUTILUS MACROMPHALUS: GROWTH RATE AND AGE OF MATURITY

N. H. Landman, Ellen R. M. Druffel, J. Kirk Cochran, D. J. Donahue and A. J. T. Jull

The chambered nautilus is the only surviving member of a large group of extinct shelled cephalopods and, as such, details of its life history are important to the understanding of this group. Yet data on its natural growth rate and age at maturity are sparse. Estimates based on mark-recapture studies of Nautilus belauensis have suggested that this species may reach maturity at 15-17 years and may live for several years longer. Estimates based on naturally-occurring radionuclides in the same species have suggested an age at maturity of approximately 10 years. However, both these estimates are calculated by extrapolating rates of growth determined over a 2 to 3 year period of ontogeny. an alternative approach is provided by the temporal pattern of bomb-produced radiocarbon observed in the world ocean. This pattern, as recorded in banded corals, consists of a marked increase in $\Delta^{14}C$ between 1958 and 1970 as a result of atmospheric testing of atomic weapons. Using tandem accelerator mass spectrometry (TAMS), we determined the pattern of $\Delta^{14}C$ in a shell of a mature specimen of N. macromphalus. The pattern is similar to that in corals and indicates that the age of maturity of this species is approximately 10-12 years.

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WHOI Contribution No. 6507.

## $\delta^{13}C$, $TCO_2$, AND THE METABOLISM OF ORGANIC CARBON IN DEEP SEA SEDIMENTS

Frederick L. Sayles and William B. Curry

The stoichiometry and rates of benthic sediment metabolism at five stations have been determined on the basis of the carbon released to the pore waters as $TCO_2$. The stations cover a range of redox conditions permiting an evaluation of stoichiometry in oxic environments and under conditions where both denitrification and manganese reduction occur. At four of the five stations the $TCO_2$ added to the pore waters is significantly enriched in $^{13}C$ relative to predictions from traditional Redfield ratio based stoichiometry. Consideration of a variety of factors indicates that the heavy isotopic composition results from neutralization of inorganic $CO_3^{2-}$ ion in excess of prediction.

Inorganic $CO_3^{2-}$ ion appears to originate from two sources, $CaCO_3$ dissolution and diffusion of $CO_3^{2-}$ into the sediments from the overlying water. The latter is estimated to amount to 1/4 to 1/3 of the $TCO_2$ derived from inorganic sources. Even at well below the interface, $Ca^{2+}$ enrichments, taken to represent $CaCO_3$ dissolution, are insufficient to balance added inorganic $TCO_2$ as determined from $\delta^{13}C$ composition.

Rates of sub-oxic diagenesis, determined from flux estimates across redox boundaries, are usually small compared to oxic rates. However, at the most reduced stations studied sub-oxic rates are quite substantial, amounting to 30-45% of the total.

In press: Geochimica et Cosmochimica-Acta.

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WHOI Contribution No. 6527.

## RARE EARTH ELEMENTS IN THE SEDIMENTS OF THE NORTH ATLANTIC OCEAN, AMAZON DELTA, AND EAST CHINA SEA: REINTERPRETATION OF TERRIGENOUS INPUT PATTERNS TO THE OCEANS

Edward R. Sholkovitz

New and published data for the concentration and relative abundances of rare earth elements (REE) are synthesized for the sediments of the North Atlantic Ocean, and coastal regions off China. The new data come from the shelf, slope, and abyssal regions off North America, the delta of the Amazon River, and the East China Sea and Yellow Sea shelves. Shale-normalized REE patterns are consistently and significantly (1.8 to 2.0 times) enriched in light and intermediate REE relative to heavy REE (HREE). This obser-

vation is consistent with the limited amount of REE data for riverine particles and casts doubt on the underlying assumption used in the interpretation of oceanic REE data - a flat shale-normalized pattern for the terrigenous input of particulate REE to the oceans.

Profiles of REE from box cores on the slope off New England display no diagenetic signal associated with large diagenetically-induced surface enrichments in Mn. No cerium anolamies are observed in these sediments.

The conclusion of Thomson et al. (1984) that there is preferential authigenic removal of light REE (LREE) onto red clays in the Nares Abyssal Plain is reassessed. Based on the direct comparison of their grey and red clay REE data, with the exception of Ce, there is no distinguishable fractionation of LREE from HREE at this location.

In press: American Journal of Science.

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WHOI Contribution No. 6459.

## THE CYCLING OF DISSOLVED RARE-EARTH ELEMENTS IN CHESAPEAKE BAY

Edward R. Sholkovitz and Harry Elderfield

The measurement of dissolved rare earth elements (REE) in the surface waters, water column of anoxic basins, and pore waters in Chesapeake Bay has provided new insights into the biogeochemistry and estuarine chemistry of REE. All dissolved REE from the riverine source show large scale removal in the lower salinity zone (0-10°/$_{oo}$); the light REE (LREE) are removed to a greater extent than are the heavy REE (HREE) (80-90% vs. 60%). The shale-normalized pattern of dissolved Susquehanna River water is opposite in form to that of surface sediments in the Bay. The former are enriched in HREE while the latter are enriched in LREE. Neither component has a flat pattern normally assumed for river-transported REE to the ocean. These data have important implications for the interpretation of REE patterns and cycling in the marine environment.

The dissolved LREE (i.e., La, Ce, Nd, Sm, Eu) are enriched (three-to-nine times) in the anoxic deep waters of over their concentrations in the oxic surface waters. In contrast, HREE (Er, Yb, Lu) are slightly depleted.

All REE concentrations in the two surface (0-2 cm) pore waters are greatly enriched (8-17 times; 43 times for Ce) relative to anoxic bottom waters and have relative abundances opposite to those of their sediments. While Ce has a positive anomaly in the pore waters, negative anomalies exist in the anoxic bottom waters.

The REE are participating in a set of complex biogeochemical cycles within the water column and surface sediments. Fractionation of REE during these cycles leads to the preferential enrichment of LREE in the seasonally anoxic bottom waters. It is proposed that this fractionation is coupled to redox cycles of Mn and Fe and the interaction of dissolved REE with suspended particles and surface sediments.

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WHOI Contribution No. 6600.

## TRACE ELEMENT ANALYSES OF THE ALLENDE METEORITE REFERENCE SAMPLE BY EMISSION SPECTROMETRY

Geoffrey Thompson

Two splits from the Allende Meteorite Reference Sample were analyzed for trace element composition. Results were obtained by direct-reading optical emission spectrometry with d.c. arc excitation.

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WHOI Contribution No. 6679.

## HYDROTHERMAL MINERALIZATION ON THE MID-ATLANTIC RIDGE

Geoffrey Thompson, Susan E. Humphris, Brian Schroeder, Margaret Sulanowska, and Peter A. Rona

Two active black smoker-type hydrothermal vent sites on the Mid-Atlantic Ridge at 26°N (TAG) and 23°N (Snakepit) have recently been discovered at depths of 3700 and 3500 m, respectively. The two sites differ from each other in their geologic setting, with the TAG site being located on older sedimented crust a few km from the spreading axis at the junction of the rift valley floor and the east wall. The Snakepit site is located on the top of a large volcanic ridge (40 km long, 600 m high) in the axial zone of the rift valley. The TAG site is the larger of the two and probably older and more mature.

Both sites show a varied thermal struc-

ture and range in temperature of venting solutions from shimmering water, through white smokers (226°C) to black smokers (335°C to 350°C). Hydrothermal solutions have similar chemical compositions to those measured on the East Pacific Rise and apparently do not show evidence of phase transition. Mineralization is similar to that occurring on faster spreading ridges, e.g., the dominant polymetallic sulfides are pyrite, pyrrhotite, chalcopyrite and sphalerite, and anhydrite is the dominant sulfate. They differ from the East Pacific and Juan de Fuca sites in having little or no barite, very little amorphous silica and abundant aragonite as a late stage recipitate. Diagenesis and weathering, particularly at the TAG site, has produced abundant amorphous iron oxides and hydroxy-oxides, goethite, hematite, atacamite, jarosite and sulfur. The active black smokers of the Snakepit site have pyrrho-tite as the dominant sulfide phase but it is absent from the active chimneys at TAG. Zinc sulfide occurs as the predominant phase in the white smoker, lower tempera-ture regions at both sites.

In press: Canadian Mineralogist.

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WHOI Contribution No. 6529.

## NITRIFICATION AND NITRIC OXIDE IN THE OXYGEN MINIMUM OF THE EASTERN TROPICAL NORTH PACIFIC

B. B. Ward and Oliver C. Zafiriou

Ammonium oxidation rates ($V_{NH4}$), nitric oxide concentrations [NO], and NO formation rates ($V_{NO}$) were measured below the euphotic zone off Baja California. Vertically-integrated nitrification rates were 1.1 to 2.7 mM N $m^{-2}d^{-1}$, compared with VERTEX estimates in a nearby region of 0.56 mM $m^{-2}d^{-1}$ for the loss of sink-ing organic N between 100 m and 2000 m. Integrated ammonium oxidation rates may thus provide valid independent estimates of organic N recycling.

NO was detected at subnanomolar levels throughout the water column at oxygen con-centrations between 0 and 100 µM. Many samples actively generated NO, which re-quired an in situ source, and yielded flux estimates. A crude estimate of the verti-cally-integrated NO flux for the region, 0.19 mM N $m^{-2}$, is 13% of the average integrated nitrification flux, suggesting the NO plays a significant role as an intermediate in the nitrogen cycle.

Most NO and NO production was found in the region of active nitrification outside the zone of active denitrification. How-ever, the measured quantities are inter-related in a complex way that suggests, but does not prove, that a link between the two exists. Some evidence suggests that NO arises from an intermediate fil-terable through 0.2 µm filters, possibly a soluble byproduct of nitrification.

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WHOI Contribution No. 6477.

# DEPARTMENT OF GEOLOGY AND GEOPHYSICS

David A. Ross, Chairman

## REPLY TO COMMENT ON "KINEMATIC AND DYNAMIC ESTIMATES FROM ELECTROMAGNETIC CURRENT METER DATA" by R.T. Guza

D. G. Aubrey

Guza [this issue] (hereafter Guza) has raised some issues with the findings of Aubrey et al. [1984] and Aubrey and Trowbridge [1985] (henceforth AST and AT, respectively) regarding the use of Marsh-McBirney (MMI) electro-magnetic current meters (EMCM) in nearshore environments. At least one other recent article [Doering and Bowen, 1987] addresses the field performance of electro-magnetic current meters, in part motivated by the AST studies. To clarify the issues raised, this reply addresses some of the major concerns of these authors. To simplify the presentation, this reply follows the outline of Guza in a systematic fashion. It will become clear that at least a significant part of the concerns raised by Guza are based on inferences drawn from AST and AT rather than on direct statements and on the failure of these latter authors to balance their reporting of laboratory analyses with results from existing field data intercomparisons.

In press: Journal of Geophysical Research.

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WHOI Contribution No. 6641.

## CHANGING COASTAL LEVELS OF SOUTH AMERICA AND THE CARIBBEAN REGION FROM TIDE-GAUGE RECORDS

D. G. Aubrey, K. O. Emery and E. Uchupi

Tide-gauge records from southern Mexico, the Caribbean Islands, and Central and South America that span the interval 1940-1970 reveal long-term changes of relative sea level according to regression analysis and eigenanalysis. The results indicate such large variations in both direction and rate of secular movement as to rule out changes in volume of ocean water as being more than a subordinate factor. The only satisfactory explanation is that the land level beneath the tide gauges is rising in some places and sinking in others.

Complex spatial patterns of relative sea-level change in southern Mexico and the Caribbean mirror the tectonic regime of these regions, exhibiting both submergence and emergence of the land. Central American tide-gauge records similarly show considerable complexity, responding to relative movement along plate boundaries. The Pacific coast of South America appears to correlate with the depth of the Benioff zone; subduction of aseismic ridges produces local highs in the Benioff zone, flanked by troughs at either side. Near the Benioff highs, relative land level is rising; between these ridges relative land level is falling. Sea-level trends in southern and Atlantic coasts of South America are closely linked with continental crustal rifting and subsidence. Data do not allow unambiguous separation of changes in ocean level from changes in land level, and no simple eustatic ocean level change can be estimated accurately from these data.

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WHOI Contribution No. 6148.

## SEASONAL CLIMATOLOGY OF TIDAL NON-LINEARITIES IN A SHALLOW ESTUARY

David G. Aubrey and Carl T. Friedrichs

Hourly sea levels recorded over a 16-month period at eight tide gauges throughout the estuarine system at Murrells, South Carolina, clarify the climatology of tidal distortion within this shallow, well-mixed estuary. Numerical results are consistent with these data and suggest comparable behavior in other geometrically-similar systems. The non-linear tidal response to changes in the amplitude-to-depth ratio (a/h) are investigated utilizing the spring-neap cycle over a single month and the offshore steric response over an entire year or more. As a/h increases in Murrells estuary due to greater tidal amplitude, tidal distortion becomes more flood dominant. However, patterns of non-linear tidal distortion in response to lower frequency ocean level change are strongly dependent upon proximity to local concentrations of intertidal flats. In areas of small tidal flat extent, as a/h decreases (due to rising sea level), tidal distortion becomes less flood dominant; in areas of extensive flats, absolute distortion and, therefore, flood dominant nature grows with greater h.

Numerical modeling of estuary sea height and tidal velocity support the observations, which are consistent with the hypotheses of Aubrey and Speer (1985) and Speer and Aubrey (1985). They also have implications for changes in estuarine response to accelerates sea-level rise in the near future.

In press: Springer-Verlag Lecture Notes on Coastal and Estuarine Studies.

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WHOI Contribution No. 6644.

## PALEOGENE GEOCHRONOLOGY: An Integrated Approach

M-P. Aubry, W.A. Berggren, D.V. Kent, J.J. Flynn, K.D. Klitgord, J.D. Obradovich and D.R. Prothero

Geochronology is the conceptual division of continuous time as measured (geochronometry) by the progression in an ordinal series of events. This is best achieved by an approach which integrates four independent data sets: magnetostratigraphy, sea-floor spreading magnetic lineation patterns, biostratigraphy, and isotopic ages. This integrated approach results in an ordinal framework which can measure time with greater resolution, though perhaps less accuracy, than a radiometric approach alone. A comparative analysis of two recently proposed Paleogene geochronologic time-scales is presented.

Supported by: NSF Grant OCE84-17040.

WHOI Contribution No. 6441.

## MORPHOLOGY AND STRUCTURE OF THE AMIRANTE TRENCH, WESTERN INDIAN OCEAN: IMPLICATIONS FOR TRENCH ORIGIN

John E. Damuth and David A. Johnson

The Amirante Trench is an arcuate 600 km long and up to 5200 m deep topographic depression whose origin has remained enigmatic. The trench together with the adjacent volcanic Amirante Ridge resemble an oceanic arc-trench system and some previous investigators have suggested that this complex represents some type of subduction zone. However, careful analysis of bathymetric and structural data indicate that the trench is not a simple, continuous arcuate feature, but is actually a compound feature composed of three discrete, essentially linear segments of differing structural orientations and probable sea-floor spreading origins: (1) The northern segment (4°20'-6°20'S) trends northeast (~030°) and apparently represents a fracture zone or transform-fault trend related to sea-floor spreading in the Mascarene Basin during the late Cretaceous. (2) The central segment (6°20'-8°40'S) trends north-northwest (~350°) and possibly represents a fracture-zone lineament related to the opening of the Somali Basin and the southerly motion of Madagascar away from Africa during the late Jurassic and early Cretaceous. (3) The southern segment (8°40'-10°S) trends northeasterly (~310°) and may represent tensional rifting related to sea-floor spreading within the Mascarene Basin during the early Tertiary. Further, our data show no convincing evidence that any portion of this feature was a subduction zone at any time during its development. In addition, the data essentially rule out an extra-terrestrial impact origin for this region at the end of the Cretaceous.

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WHOI Contribution No. 6688.

## MARINE GEOLOGY OF THE SOHM BASIN

Cynthia J. Ebinger and Brian E. Tucholke

Multichannel seismic reflection, seismic refraction, and magnetic anomaly data have been used to study the Mesozoic-Cenozoic seafloor-spreading and depositional history of the Sohm basin, which includes the Sohm Abyssal Plain and the continental rise southeast of Nova Scotia (Canada). To constrain the age of basal seismic sequences at their pinchouts on oceanic crust, the age of oceanic lithosphere beneath the Sohm basin has been dated by the identification of Mesozoic (M-series) magnetic anomalies. Comparison to previously identified Mesozoic magnetic anomalies on the Bermuda Rise and to modeled anomalies shows that crust was generated at very slow sea floor spreading rates (5-15 mm/yr half rates). The slow spreading rates and deep burial of the oceanic crust explain the low-amplitude, low-frequency character of Sohm basin magnetic anomalies without requiring an abnormal magnetic source layer. Very rough oceanic basement topography was generated at the slow-spreading ridge, but the

thickness and seismic-velocity structure of the crust is typical of "normal" oceanic crust. Basement depths corrected for sediment loading fall below the predicted age/depth curve in the M2-M25 interval. These depth anomalies and an associated regional negative geoid anomaly may reflect long-wavelength mantle convection patterns beneath the basin.

We have correlated prominent seismic horizons and seismic sequence boundaries in the Sohm basin with established seismic and deep well stratigraphies on the Nova Scotian shelf and in the western North Atlantic basin south of the New England seamounts. These identifications, as well as the ages of oceanic crust where the seismic horizons pinch out seaward, provide a chronology for interpretation of the seismic sequences. The Jurassic to Lower Cretaceous sequences are similar in thickness and acoustic character to sequences observed along the U.S. Atlantic margin, suggesting that the New England seamounts did not pose a significant barrier to sediment distribution patterns along the continental margin. Late Cretaceous sediment flux to the Sohm basin was extremely limited due to flooding of the continental margin during the eustatic sea-level rise, and possibly because salt tectonics uplifted a sedimentary ridge which blocked seaward sediment transport onto the lower continental rise.

Progradational sedimentary wedges and erosional unconformities characterize the Tertiary sedimentary record along the lower continental rise of Nova Scotia. These prograding sequences generally correlate to times of sea level lowstands that are documented in the Nova Scotian shelf sequences and along the U.S. Atlantic continental margin. Repeated episodes of erosion by abyssal currents are marked by the seismic unconformities Horizon $A^u$ (early Oligocene), LM (early Miocene), and MM (middle Miocene), and L (late Pliocene). In addition to the erosional sculpting of the continental rise, the currents have controlled local patterns of deposition and have modified cross-slope transport and sediment accumulation patterns. Thick post-Horizon L sediments blanket the Sohm basin and reflect rapid sediment influx caused by Quaternary glacio-eustatic fluctuations.

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Contribution No. 6511.

## COASTAL NEO-TECTONICS OF THE MEDITERRANEAN FROM TIDE-GAUGE RECORDS

K.O. Emery, D.G. Aubrey and V. Goldsmith

Records from tide gauges in Israel and Egypt have not been examined carefully during the past in spite of many geological and archaeological investigations that contributed information about relative sea-level changes. Seven such records reveal changes during the past few decades that accord with prior inferences about land movements in this region (emergence along the coast of Israel and at Alexandria and subsidence at the Nile Delta and the head of the Gulf of Suez). Twenty-four other tide-gauge records for the rest of the Mediterranean region indicate more uniformity (submergence of land or rise of sea level) in the west, but with greater movements of the land attributed to plate underthrusting in Turkey and Greece, to volcanism near Mount Etna, to deltaic compaction at Izmir, and to deltaic compaction coupled with water pumping at the Po Delta.

In press: Marine Geology.

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WHOI Contribution No. 6620.

## PARTICLE FLUX IN THE WESTERN BLACK SEA THROUGHOUT THE PAST 5,000 YEARS WITH COMPARISON OF THE PRESENT FLUX

Bernward Josef Hay and Susumu Honjo

The particle flux over the last 5,000 years (paleoflux) was studied in detail from core samples of the western Black Sea. Results were compared to a 2 1/2 year long time-series particle flux study with sediment trap in the southwestern Black Sea.

Compared to the present-day particle flux in the southwestern Black Sea, the paleoflux over the last 1,000 years in the western Black Sea is higher by a factor of 5.5, mostly because of an 11 times higher carbonate paleoflux; the paleoflux of lithogenic particles is higher only by a factor of 3. Most of the variability in the paleoflux is a function of the variability in the supply of coccoliths from Emiliania huxleyi. The contrast between paleoflux and present-day particle flux in the southwestern Black Sea is a function of different parameters in the particle supply. Particles in the central part of

the western Black Sea are supplied predominantly from the northwestern shelf while particles in the southwestern Black Sea are supplied from the Anatolian mountains. The paleoflux between 1,000 and 5,000 years B.P. (unit II) is lower by a factor of 3 compared to the last 1,000 years (unit I). Most of the variability in the paleoflux in unit II is a result of the variability in the supply of terrigenous matter.

Comparison of the laminated core sediments with seasonal dynamics in particle supply in the southwestern Black Sea suggests that white laminae (over 90% carbonate) formed during summer and fall, whereas black laminae (mostly clay minerals) formed during winter and spring.

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WHOI Contribution No. 6656.

## STATISTICAL METHODS FOR DESCRIBING SEAFLOOR TOPOGRAPHY

Peter R. Shaw and Deborah K. Smith

We present a method for objectively characterizing a swath of digitally sampled seafloor topography. Our method analyzes the distribution of surface slopes by projecting the surface-normal vectors onto a two-dimensional histogram using an equalarea projection. The direction of maximum variance (first principal axis) of the histogram is used to determine the azimuth of lineations in the topography, and the variance is used as a measure of seafloor roughness. We apply the method to short sections of Sea Beam swath data and find that the histogram parameters are effective in describing the behavior of the topography. In particular, similar patterns are observed for a sequence of histograms derived from data collected over the Mendocino and the Surveyor fracture zones in the northeast Pacific. Because the method does not require any data modification, and is suitable for irregularly-shaped sample regions, it lends itself to real-time analysis.

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WHOI Contribution No. 5640.

## SEAMOUNT STATISTICS IN THE PACIFIC OCEAN

Deborah K. Smith and Thomas H. Jordan

We apply the wide-beam sampling technique of Jordan et al. (1983) to approximately 157,000 km of wide-beam profiles to obtain seamount population statistics for eight regions in the eastern and southern Pacific ocean. Population statistics derived from wide-beam echograms are compared with seamount counts from Sea Beam swaths and with counts from bathymetric maps. We find that the average number of seamounts with summit heights $h \geq H$ is well-approximated by the exponential frequency-size distribution: $v(H) = v_o e^{-\beta H}$. The exponential model for seamount sizes, characterized by the single scale parameter $\beta^{-1}$, is found to be superior to a power-law (self-similar) model, which has no intrinsic scale, in describing the average distribution of Pacific seamounts, and it appears to be valid over a size spectrum spanning five orders of magnitude in abundance. Large-scale regional variations in seamount populations are documented. We observe significant differences in seamount densities across the Murray fracture zone in the North Pacific and the Eltanin fracture zone system in the South Pacific. The Eltanin discontinuity is equally evident on both sides of the Pacific-Antarctic ridge. In the South Pacific, regions symmetrically disposed about the ridge axis have very similar seamount densities, despite the large difference between Pacific-plate and Antarctic-plate absolute velocities; evidently, any differences in the shear flows at the base of the Pacific and Antarctic plates do not affect seamount emplacement. Systematic variations in $v_o$ and $\beta$ are observed as a function of lithospheric age, with the number of large seamounts increasing more rapidly than small seamounts. These observations have been used to develop a simple model for seamount production under the assumptions that (1) an exponential size-frequency distribution is maintained, (2) production is steady-state, and (3) most small seamounts are formed on or near the ridge axis. The limited data available from this study appear to be consistent with the model, but they are insufficient to provide a rigorous test of the assumptions or determine accurately the model parameters. However, the data from the South Pacific indicate that the off-axis production of large seamounts probably accounts for the majority of seamounts with summit heights greater than 1000 m.

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Contribution No. 6484.

## THE SIZE DISTRIBUTION OF PACIFIC SEAMOUNTS

Deborah K. Smith and Thomas H. Jordan

An analysis of wide-beam, Sea Beam and map-count data in the eastern and southern Pacific confirms the hypothesis that the average number of "ordinary" seamounts with summit heights $h \geq H$ can be approximated by the exponential frequency-size distribution: $v(H)=v_o e^{-\beta H}$. The exponential model, characterized by the single scale parameter $\beta^{-1}$, is found to be superior to a powerlaw (self-similar) model. The exponential model provides a good first-order description of the summit-height distribution over a very broad spectrum of seamount sizes, from small cones ($h<300$m) to tall composite volcanoes ($h>3500$m). The distribution parameters obtained from 157,000 km of wide-beam profiles in the eastern and southern Pacific are $v_o=(5.4\pm0.65) \times 10^{-9} m^{-2}$ and $\beta=(3.5\pm0.21)\times10^{-3} m^{-1}$, yielding an average of 5400 $\pm$ 650 seamounts per million square kilometers, of which 170 $\pm$ 17 are greater than one kilometer in height. The exponential distribution provides a reference for investigating the populations of not-so-ordinary seamounts, such as those on hot-spot swells and near fracture zones, and seamounts in other ocean basins. If we assume that volcano height is determined by a hydraulic head proportional to the source depth of the magma column, then our observations imply an approximately exponential distribution of source depths. For reasonable values of magma and crustal densities, a volcano with the characteristic height $\beta^{-1}=285$m has an apparent source depth on the order of the crustal thickness.

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## A BRIEF COMMENTARY ON THE MESOZOIC-CENOZOIC GEOLOGIC EVOLUTION OF IBERIA, A TECTONIC LINK BETWEEN AFRICA AND EUROPE

Elazar Uchupi

The present familiar configuration of the earth with its pattern of oceans, inland seas, and continents is the end result of the random wandering and collision of plates, a pattern that has been repeated endlessly throughout geologic time. In this brief geopoetic saga I will attempt to describe how Iberia came to be what it is today. I illustrate this evolution with the aid of sixteen paleogeographic maps from the Late Permian to the present compiled from the primary sources listed in the references. With this brief summary I have included four of these maps; one for the Late Triassic rifting phase, another for the Early Cretaceous (Aptian) when Iberia separated from North America and Europe, a third for the middle Eocene when Iberia and Europe collided (Pyrenean orogeny), and a fourth for early Miocene when Africa began to collide with Iberia and the Balearic Basin started to open (Figs. 1-4). For a more detailed discussion the reader is referred to the longer paper to be published by the Congress.

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WHOI Contribution No. 6557.

## RELATIONSHIPS OF ENVIRONMENTAL FACTORS TO TOXIC DINOFLAGELLATE BLOOMS IN THE BAY OF FUNDY

Alan W. White

Shellfish toxicity data for the Bay of Fundy extend back to 1944, representing the longest time series of this kind in the world. The data reflect the abundance of the toxic dinoflagellate Gonyaulax excavata in the water and thus the pattern of its annual blooms over the years. Relationships between shellfish toxicity and environmental data over the 40-year period are being examined. Results at this stage show some significant correlations between environmental factors during pre-bloom months and summer toxicity. Correlation with the 18.6-year cycle of lunar modulation of the tide is of particular interest. Pre-bloom environmental variables account for 28-97% of the variation in summer toxicity, but only a few of the correlations are statistically significant ($P<0.05$).

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## MORTALITY OF FISH LARVAE FROM EATING TOXIC DINOFLAGELLATES OR ZOOPLANKTON CONTAINING DINOFLAGELLATE TOXINS

Alan W. White, Osamu Fukuhara and Masateru Anraku

First-feeding red sea bream (Pagrus major) and Japanese anchovy (Engraulis japonica) larvae were fed the toxic dinoflagellate Gonyaulax excavata. Older larvae were fed zooplankton (mostly copepods) that had eaten G. excavata. Despite low toxin content of the dinoflagellates relative to field conditions, effects of the toxins were apparent. The mortality rate of first-feeding red sea bream larvae feeding on Gonyaulax was about three times that of starved controls. First-feeding Japanese anchovy larvae fed poorly on Gonyaulax, and no difference in mortality between treatments and controls was observed. Older larvae of both species showed symptoms typical of "paralytic shellfish poisoning" within a few hours after eating zooplankton that contained Gonyaulax toxins; 20 to 30% of the larvae died. Results indicate that fish larvae, like adult fish, are sensitive to paralytic shellfish toxins and suggest that blooms and red tides of G. excavata and its toxic relatives cause kills of larval, as well as adult, fish.

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WHOI Contribution No. 6647.

# G E O P H Y S I C S

## SEISMIC ENERGY PARTITIONING AND SCATTERING IN LATERALLY HETEROGENEOUS OCEAN CRUST

Martin E. Dougherty and Ralph A. Stephen

We present finite difference forward models of elastic wave propagation through laterally heterogeneous upper oceanic crust. The finite difference formulation is a 2-D solution to the elastic wave equation for heterogeneous media and implicitly calculates P and SV propagation, compressional to shear conversion, interference effects and interface phenomena. Random velocity perturbations with Gaussian and self-similar autocorrelation functions and different correlation lengths (a) are presented which show different characteristics of secondary scattering. Heterogeneities scatter primary energy into secondary body waves and secondary Stoneley waves along the water-solid interface. The presence of a water-solid interface in the models allows for the existence of secondary Stoneley waves which account for much of the seafloor 'noise' seen in the synthetic seismograms for the laterally heterogeneous models.

'Random' incoherent secondary scattering generally increases as ka (wavenumber, k, and correlatin length, a) approaches one. Deterministic secondary scattering from larger heterogeneities is the dominant effect in the models as ka increases above one. Secondary scattering also shows up as incoherence in the primary traces of the seismograms when compared to the laterally homogeneous case. Cross-correlation analysis of the initial P-diving wave arrival shows that, in general, the correlation between traces decreases as ka approaches one. Also, because many different wave types exist for these marine models, the correlation between traces is range dependent, even for the laterally homogeneous case.

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WHOI Contribution No. 6686.

## U.S. ATLANTIC CONTINENTAL MARGIN: STRUCTURAL AND TECTONIC FRAMEWORK

K.D. Klitgord, D.R. Hutchinson and Hans Schouten

The U.S. Atlantic continental margin (Fig. 1) is the type-example of a passive (Atlantic-type) continental margin which has developed on the edge of an ocean basin evolving between two separating continents (Bally, 1981; Grow and Sheridan, 1981). As the U.S. margin evolved through compressional, extensional, and vertical (subsidence) tectonic phases, a distinctive set of deep crustal structures, basement structures, and sedimentary features were created. The series of Paleozoic orogenies, which created the Appalachian mountains, formed crustal-penetrating thrust faults, accreted-terrane boundaries, and magmatic structures that would control the locus of crustal fracturing during the subsequent extensional phase. During the rifting phase, the margin was an active plate margin as

the African plate started to break away from the North America plate. Only during the subsidence phase is an Atlantic-type margin actually a passive continental margin. The very thick sedimentary wedge overlying crystalline basement on the margin limits our knowledge of basement and underlying crustal structures, but it also provides a detailed record of the subsidence phase of margin evolution. Distinctive magnetic-anomaly and gravity-anomaly lineations, discontinuities, and characteristic patterns also developed during the evolution of this margin. These geophysical anomalies provide the basis for inferring crustal structures and crustal types in lieu of more direct seismic or sample information.

Models for the evolution of Atlantic-type continental margins have been developed from studies of other extensional-tectonic regimes, such as the southern Australian margin (Falvey, 1974; Falvey and Middleton, 1981), Biscay margin of France (Montadert and others, 1979; LePichon and Barbier, 1987), the North Sea (McKenzie, 1978; Sclater and Christie, 1980), and the Basin and Range province (Anderson and others, 1983; Wernicke, 1985). Applications of subsidence models to the U.S. and Canadian Atlantic margins (Watts, 1982; Steckler and Watts, 1982; Keen, 1982; Sawyer and others, 1983; Steckler and others, this volume) have successfully enhanced our ability to interpret the sedimentary record of the postrift evolution of the margin. New models for the mechanical deformation during rifting and subsidence phases are just now being developed (e.g. Bally, 1981; Wernicke, 1985; Lister and others, 1986; LePichon and Barbier, 1987). Kinematic evolution of the atlantic in a plate-tectonic framework (Klitgord and Schouten, 1986) provides an additional constrains on margin evolution models by locating active plate boundaries relative to the margin during the rifting and then passive margin phases.

A considerable volume of information now exists for the crustal structure of the U.S. Atlantic margin. Summaries of structural studies, as they apply to individual segments of the margin, can be found in subsequent chapters. In this chapter we examine the geophysical framework, general structural framework, deep crustal framework, and then the plate tectonic framework of the Atlantic margin. We shall outline the important structural elements and geophysical lineaments that have been identified and mapped along the margin. We conclude with discussion of margin evolution which includes this structural information as well as newly developed rift margin evolution models.

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WHOI Contribution No. 5633.

## DETAILED MAGNETIC STUDY OF THE REYKJANES RIDGE BETWEEN 63°00'N AND 63°40'N

Jean-Christophe Sempere,
Leo Kristjansson, Hans Schouten,
James R. Heirtzler and G. Leonard Johnson

Immediately southwest of Iceland the Reykjanes Ridge consists of a series of en échelon, elongated ridges superposed on an elevated, smooth plateau. Johnson and Jakobsson (1985) have suggested that the Reykjanes Ridge on the Icelandic insular shelf between 62°55'N and 63°48'N is made up of 8 separate submarine volcanic systems. We have interpreted a detailed magnetic study of this portion of the Reykjanes Ridge. Because water depths are extremely shallow in the survey area (~100-500m), the surface magnetic survey is equivalant to a high sensitivity, near-bottom experiment using a deeply-towed magnetometer. To remove the distortion induced in the magnetic field by the skewness of the Earth's field and by bathymetric effects, we have performed 2-D inversions of the magnetic data along profiles perpendicular to the volcanic ridges. The inversions, which yield the magnetization distribution responsible for the observed magnetic field, allow us to locate the zones of most recent volcanism and to measure spreading rates accurately. We estimate the average spreading rate over the last 0.72 m.y. to have been 10 mm/yr within the survey area. Despite an increase in the iron and titanium content of the basalts along the Reykjanes Ridge toward Iceland (Schilling, 1973; Johnson and Jakobsson, 1985), the magnetization intensities we obtain are low, probably as a result of the oxidation of the titanomagnetite associated with degassing at low confining pressures. The 2-D inversions also allow us to measure polarity transition widths which provide an indirect measure of the width of the zone of crustal accretion. We find a mean transition width of the order of $4.5 \pm 1.6$km. The observed range of transition widths (2 to 8.4 km) and their mean value are characteristic of slow spreading centers where the locus of crustal accretion is prone to lateral shifts depending on the availability of magmatic sources. These results suggest that, despite its unique volcano-tectonic setting, the scale at which crus-

tal accretion occurs along the Reykjanes Ridge may be similar to that at which it occurs along other slow spreading centers.

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WHOI Contribution No. 6606.

## AN INVESTIGATION OF SMALL-OFFSET FRACTURE ZONE GEOID WAVEFORMS

Peter R. Shaw

Approximately 1,500 geoid cross sections across 15 small-offset South Atlantic fracture zones (FZ's) are compiled from Seasat altimeter data and organized according to crustal age; these profiles provide a basis for the comparison of the different FZ's, and the evolution of each over geological time. I use an empirical orthogonal function decomposition to investigate the dependence of profile shape and amplitude upon crustal age. The geoid cross sections are found to be coherent in form down the length of each FZ, and possess amplitudes that are inversely related to the relative spreading rate at the time of formation. This observation is consistent with a simple model in which the active portion of a fracture zone (the transform fault) remains a fixed spatial length, yielding a variable age offset across the FZ.

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WHOI Contribution No. 6645.

## WAVEFORM INVERSION OF TIME-CORRECTED REFRACTION DATA

Peter R. Shaw

Seismic refraction data collected in land or marine surveys are often complicated by small, near-random time shifts of the individual seismograms relative to one another. For the case of fixed-receiver geometry, these shifts arise, primarily from basement topography, often masked by sediments, beneath each source. Although a topographic timing correction is normally applied to the seismograms, the effects of poorly-known topography produces residual shifts in the seismograms. The application of additional time corrections (statics) can bias solutions computed using iterative wave-form inversion, because a suitable set of statics can make a poor starting velocity model appear to match the data. Without any correction, however, seismograms computed from even the best-fitting laterally homogeneous model may not agree with the data to within one-half period. In this paper I present a formalism for iterative waveform inversion of refraction data containing residual time shifts. In this method the statics are directly modelled in the synthetic seismograms and new values estimated in the inversion together with new velocity model parameters. The method is similar to studies of statics in seismic reflection data, but here, values for the statics are estimated simultaneously with the velocity model; with the use of suitable norms the new velocity model is required to be smooth and the statics required to be small. Convergence is achieved when the velocity profile's roughness, the rms size of the statics, and the waveform misfit are in equilibrium. Because the starting synthetics need not match the data to within one-half period, a much larger set of velocity models used for an initial guess will converge on the family of solutions than for waveform inversions in which time shifts are not used. The original, arbitrary starting model loses its importance after the first iteration and solutions meeting the convergence criterion appear to be independent of the particular choice of starting model. Numerical tests show the method to be robust: an inaccurate starting model that fits the data only through a biased set of statics is accurately corrected. The method is illustrated on a set of refraction data collected in the vicinity of the East Pacific Rise. In this application two quite different starting velocity models converge to a common family of solutions.

In press: Geophys. J. R. astr. Soc.

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WHOI Contribution No. 6572.

## STRUCTURE OF UPPER OCEANIC CRUST FROM AN OBLIQUE SEISMIC EXPERIMENT AT SITE 418A, WESTERN NORTH ATLANTIC

Stephen A. Swift and Ralph A. Stephen

During ODP Leg 102 to Site 418A (110 Ma, magnetic anomaly MO), a three component seismometer was clamped at five depths while shots were aligned on eight radial lines out to 8 km and on four concentric circles. Over 2200 P-wave arrival times were picked. Travel times from the radial lines were inverted to a velocity-depth profile by tau-zeta inversion and an

inflection point method. P-wave velocity increases nearly linearly at ~1.5 $s^{-1}$ from 4.5 $kms^{-1}$ at top of basement to 6.8 $kms^{-1}$ at 1.5 km depth. Below ~0.2 km our velocities are 0.25-0.5 $kms^{-1}$ less than sonic log velocities suggesting local lithology or crack porosity drilled at Site 418A may not be representative of the upper crust within ~5 km. At 0.5-1.3 km depth our velocities are ~0.25 $kms^{-1}$ less than $\tau$-$\zeta$ inversion velocities at nearby Site 417D. Travel times from shots on circular lines indicate P-wave anisotropy (180° period) of ±0.22 $kms^{-1}$ (~5%) in the upper 0.5 km that is restricted to within ~0.6 km of the hole. The horizontal symmetry axis is oblique to the paleospreading direction and rotates counter-clockwise with increasing seismometer depth. Significant anisotropy with a 180° period does not extend to greater ranges within the upper 0.5 km of crust and does not occur at 0.5-1.5 km depth over ranges of ±4-6 km.

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WHOI Contribution No. 6388.

## LATERAL HETEROGENEITY AND ANISOTROPY IN THE SEISMIC STRUCTURE OF THE UPPER OCEANIC CRUST, WESTERN NORTH ATLANTIC

Stephen A. Swift and Ralph A. Stephen

Vertical and lateral seismic velocity variations in 100 myr old oceanic crust at DSDP Site 418A were investigated with a borehole seismic experiment. A seismometer was clamped successively at 5 depths between 41 m and 430 m within the extrusive basalt layer while airgun and explosive sources were fired on 8 radial lines and on four concentric circles. Resulta of tau-zeta inversion of radial line P arrival times are supported by velocities from inflection point analysis, sonic log, and reflectivity synthetic seismograms. Velocity increases nearly linearly at 1.5 1/s from 4.6 km/s at the top of basement down to 1.5 km. Comparison with results of a similar experiment at Site 417D, 7.5 km to the north, indicates that velocities at 0.8-1.0 km depth, which represent averages over a horizontal range of 5-6 km, increase subparallel to the paleospreading axis at 0.07 1/s. Drilling results are consistent with a thinner layer of pillow flows or penetration of transition layer dikes to shallower crustal depths at Site 417D. As observed on circular lines, travel times of rays propagating in the upper 0.5 km show azimuthal anisotropy of $\pm$0.22 km/s (5%) within 0.6 km of Site 418A and a northward increase in velocity (0.36 1/s) over 4.2 km. The symmetry axis of anisotropy is oblique to the paleo-spreading axis and rotates 45° counterclockwise as the receiver depth increases from 230 m to 430 m subbasement. Models based on porosity differences due to varying degree of tectonic fracturing or mineralization of voids are inadequate. The observations are best explained by lateral variations in aligned porosity created by flow extrusion processes.

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# P A L E O C E A N O G R A P H Y

## NORTH ATLANTIC THERMOHALINE CIRCULATION DURING THE LAST 20,000 YRS: LINK TO HIGH LATITUDE SURFACE TEMPERATURE

Edward A. Boyle and Lloyd Keigwin

Advances of Northern Hemisphere ice sheets are associated with reductions in ocean surface temperatures and deep water production in the high latitudes of the North Atlantic. Previously, this association has been seen for late Quaternary sediments at resolutions upwards of several thousand years. A link between cool North Atlantic surface ocean temperatures and reduced deep water production is now shown for an event of short duration (ca. 1000-2000 years). During a brief surface cooling event 10,000 to 12,000 years ago ("Younger Dryas"), higher Cd/Ca and lower $^{13}C/^{12}C$ ratios are observed in benthic foraminifera shells from rapidly accumulating western North Atlantic sediments. These tracers reflect reduced flushing by nutrient-depleted North Atlantic Deep Water during the Younger Dryas event. Data from sediment cores representing depths from 1.5 to 4.4 km show that marked nutrient depletion of intermediate waters occurs in association with reduced glacial North Atlantic Deep Water flux. By analogy with the modern North Pacific, it is proposed that cold sea surface temperatures in the high latitude glacial North Atlantic enhance intermediate water formation at the expense of deep water formation.

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WHOI Contribution No. 6542.

## $\delta^{13}C$ IN EQUATORIAL ATLANTIC SURFACE WATERS: IMPLICATIONS FOR ICE AGE $pCO_2$ LEVELS

W. B. Curry

Carbon isotopic records of nutrient-depleted surface water place constraints on the past fertility of the oceans and on the past atmospheric $pCO_2$. The best records of nutrient-depleted $\delta^{13}C$ are obtained from planktonic foraminifera living in the mixed layers of the western equatorial and tropical Atlantic Ocean, because of their thicker nutrient-depleted, mixed layers. The power spectrum of a composite, stacked G. sacculifer $\delta^{13}C$ record from the equatorial Atlantic exhibits significant peaks at 100,000 and 40,000 year Milankovitch periods. Similar to the results presented by Shackleton and Pisias (1985), surface-deep ocean $\Delta\delta^{13}C$ produced with this record leads the $\delta^{18}O$ ice volume record. However, the glacial-interglacial amplitudes differ. Although there are large changes in $\Delta\delta^{13}C$ during early stages of the last three glacial cycles, surface-deep $\Delta\delta^{13}C$ at glacial maxima ($^{18}O$ Stage 2, late Stage 6, and late Stage 8) was only about 0.2 °/₀₀ greater than during the subsequent interglacial. Our results imply that: 1) nutrient-driven $pCO_2$ changes account for less than one half of the $pCO_2$ decrease observed in ice cores, and consequently $\Delta\delta^{13}C$ should not be used as a proxy-$pCO_2$ index; 2) enough variance in the ice core $pCO_2$ records remains to be explained that $pCO_2$-ice volume phase relationships should be reexamined; and 3) as much as 30ppm $pCO_2$ change still has not been accounted for. We propose that changes in the organic carbon:carbonate carbon rain ratio may account for the remaining unexplained variance.

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WHOI Contribution No. 6446.

## NORTH PACIFIC DEEP WATER FORMATION DURING LATEST GLACIATION

L.D. Keigwin

For at least 20 years paleoceanographers have speculated about the existence of a source of young (nutrient-depleted) deep water in the North Pacific (NPDW) during glaciations. Proof of its existence has eluded researchers because the present deep North Pacific is very corrosive to calcium carbonate. Thus, it has been difficult to obtain a long time series of oxygen isotope data on benthic foraminifera for dating the sediment, and carbon isotope data for use as a proxy for deep water nutrient content. I report here on a stable isotope record from a Western Subartic Pacific core taken at 3 km water depth. The carbon isotope ratios in the benthic foraminifera Cibicidoides show no evidence of nutrient-depleted NPDW from glacial to Holocene time.

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WHOI Contribution No. 6543.

## TOWARD A HIGH RESOLUTION CHRONOLOGY FOR LATEST MIOCENE PALEOCEANOGRAPHIC EVENTS

L. D. Keigwin

It is now widely accepted that expansion of continental glaciers is one manifestation of profound paleoenvironmental change in latest Miocene time. The oxygen isotopic record in deep sea cores is inferred to document brief pulses in glaciation, based on covariance of $\delta^{18}O$ in benthic and planktonic foraminifera, which probably lowered latest Miocene sea level by a minimum of 60 m. Additional evidence of glacial activity in the oxygen isotope record is obscured by the small signal amplitude. Before further details of paleoenvironmental change can be investigated, it is essential to have a high resolution stratigraphy and chronology. This has not been achieved previously because most studies of the latest Miocene have had a sampling interval greater than the duration of events they seek to resolve.

A high resolution stable isotope record from the North Atlantic (DSDP 552) is correlated with a lower resolution record from the Southwest Pacific (DSDP 588). Each core has magnetostratigraphy, but there are two possible interpretations of magnetic results in the Atlantic core. By assuming brief events of $^{18}O$ enrichment and $^{13}A$ depletion in each core are synchronous, it is possible to assign the most likely age model to the Atlantic core.

Results of this exercise indicate that two $\delta^{18}O$ maxima occurred 4.8 and 5.2 Ma. If these events reflect continental glaciation, and if sea level was lowered enough to contribute to isolation and desiccation

of the Mediterranean, then the Miocene-Pliocene boundary must be close to 4.8 Ma in age. This interpretation is consistent with biostratigraphy at DSDP 552; magneto-, bio-, and isotope stratigraphy at DSDP 397 (northwest African continental margin); and recent work on land in the Mediterranean region.

In press: Paleoceanography.

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WHOI Contribution No. 6573.

## P A L E O N T O L O G Y

### NEOGENE PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY AND BIOCHRONOLOGY IN BAFFIN BAY AND LABRADOR SEA

A.E. Aksu and M.A. Kaminski

During the ODP Leg 105, eleven holes were drilled at three sites in the Labrador Sea and Baffin Bay. Site 645 in Baffin Bay was drilled to a depth of 1147 m and recovered approximately 320.4 m of alternating cycles of gravel-bearing muddy sands/carbonaceous (detrital) muddy sands and silty muds/clays (lithostratigraphic Units I and II) overlaying shales, muddy sandstones and silty mudstones. In the Baffin Bay holes, planktonic foraminifers were only present in the upper 110.3 m and in a short interval between 283.8 and 293.5 m. Very low species diversity and lack of species with short stratigraphic ranges at Site 645 inhibit a planktonic foraminiferal framework to be established. Holes 646B and 647A were drilled to a depth of 766.7 and 716.6 m, respectively. Although the observed fauna in Holes 646B and 647A were not very diverse, the first and last occurrences of several age diagnostic species, together with a good paleomagnetic stratigraphy allowed a high latitude Miocene to Recent planktonic foraminiferal biochronology to be established. This biochronology is compared with the temperate-subpolar biozonations of Weaver and Clement (1986) in order to determine the relative timing of planktonic foraminiferal datum events in the eastern North Atlantic and the Labrador Sea.

In press: Initial Reports of the Deep Sea Drilling Project, Leg 105, Volume 6.

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WHOI Contribution No. 6563.

### PHYLOGENY OF THE CENOZOIC CALCAREOUS NANNOPLANKTON GENUS Helicosphaera

Marie-Pierre Aubry

Because the paleontologic concept of Coccolithophoridae species is restricted and far removed from the biologic concept which itself is not yet satisfactorily established, calcareous nannofossil taxonomy remains in an unsatisfactory state. This situation is clearly reflected by the widely different interpretations that various authors suggest of the phylogenetic relationship among species in a given genus and among genera. Examples taken from the extant genus Helicosphaera suggest that because of parallel evolution, delineation of phylogenetic relationships between coccolith morphospecies using morphologic data alone are hazardous, as is delineation of phylogenetic relationships among closely related genera.

In press: Paleobiology.

Supported by: Consortium of Oil Companies.

WHOI Contribution No. 6512.

### HANDBOOK OF CENOZOIC CALCAREOUS NANNOPLANKTON BOOK 4: HELIOLITHAE (cont.)

Marie-Pierre Aubry

Volume 4 is the first in this series which offers an internal homogeneity. It gathers calcareous nannofossils which are assign to seven different genera thought to be phylogenetically closely related. These are Placozygus, Zygodiscus, Loohodolithus. Helicosphaera, Neocrepidolithus, Pontospharea and Scyphosphaera.

Representatives of Lophodolithus, Helicosphaera and Scyohosoaera are restricted to the Cenozoic. Placozygus sigmoides (the only species of the genus Placozygus to be considered here) and species of Neocrepidolithus are represented in both the late Cretaceous and the Paleocene. Although Zygodiscus and Pontosphaera are usually regarded as strictly Cenozoic, their earliest representatives are likely to have evolved during the late Cretaceous.

These seven genera include calcareous nannofossils which share a number of (a) morphologic, (b) crystallographic (optical)

and (c) structural characters:

(a): All are primarily elliptical in outline when seen in proximal or distal view. They can be symmetrical (with two -longitudinal and transverse- axes of symmetry) or asymmetrical (with one -longitudinal- or no axis of symmetry). As seen in the light microscope, they appear as consisting of a concavo-convex thin central area surrounded by a margin of variable width and heighth (e.z. very low and narrow, low and broad, very high and thin).

(b): In cross-polarized light, they produce a characteristic black cross with extinction lines typically dextrogyre in distal view.

(c): Characteristically they are composed of three or four structural units: basal plate, flange, distal cover and transverse bar. The first two structural units are common to all coccoliths in these seven genera; the third is not well-developed in early representatives of Neocrepidolithus and in Placozygus sigmoides. The transverse bar occurs only in this latter species and in species in Zygodiscus, Loohodolithus and Helicosphaera (partim).

The basal plate forms the proximal side of the central area. It always consists of wedge-shaped radiating elements. It can be reduced to a narrow ring which delineates a large central opening as in Lophodolithus or fill entirely the central area as in Scyphosphaera.

The flange forms the proximal (outer) layer of the margin. It always consists of strongly imbricated elements (their imbrication is dextral in distal view). Except in Scyphosphaera, the flange is the back- bone of the margin of which it determines the development and the outline.

In press: Micropaleontology Press.

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WHOI Contribution No. 6445.

## PHYLOGENETICALLY BASED CALCAREOUS NANNOFOSSIL TAXONOMY: IMPLICATIONS FOR THE INTERPRETATION OF GEOLOGICAL EVENTS

Marie-Pierre Aubry

As in other fossil groups, a phylogenetically based taxonomy is a fundamental requirement for deciphering evolutionary patterns among calcareous nannoplankton. There are however difficulties associated with recognizing phylogenetically related taxonomic groups, in particular since the paleontologic concept of calcareous nannoplankton species is so far removed from the biologic concept of calcareous nannoplankton species. There are also difficulties associated with parallel and convergent evolution. Based on a discussion of the probable phylogenetic relationships between five genera (Zygodiscus, Lophodolithus, Helicosphaera, Pontosphaera and Neocrepidolithus), the status of a number of Cenozoic families are discussed, and a reinterpretation of the relationships between Mesozoic and Cenozoic calcareous nannoflora is presented.

In press: Proceedings of Second INA Meeting (Aug. 1987). Nannofossils and Their Applications (Ellis Harwood, ed.).

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## Stomiosphaera minutissima (COLOM, 1935) FROM THE LIAS OF MALLORCA (BALEARIC ISLANDS) AND UMBRIA (ITALY), AND Schizosphaerella punctulata DEFLANDRE AND DANGEARD, 1938

Marie-Pierre Aubry, Francoise Depeche and Thierry Dufour

Stomiosphaera minutissima is a junior synonym of Schizosphaerella punctulata. The dark inner layer present in the calcareous wall of S. Minutissima represents the two interlocked diagenetically modified valves of S. punctulata. The hyaline fibro-radiate outer (and sometimes inner) layer(s) is (are) of secondary origin.

In press: Geobios.

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WHOI Contribution No. 6470.

## BATHYAL BENTHICS: BACK TO BASICS

W. A. Berggren

Bathyal benthic foraminifera will assume an increasingly important economic role as petroleum exploration expands into deep water offshore regions. In order to enhance their utility in applied biostratigraphy and paleobathymetry we must improve our understanding of their basic taxonomy. This can only be accomplished by a return to basics, i.e., a comparative examination of museum-based collections in order to reduce the number of superfluous

synomynies. We must also consider the possibility of depth dependent ecophenotypy as a factor in our species concepts. The challenge ahead is great but the potential rewards even greater: a comprehensive understanding of the relation of these microbenthos in the dynamic framework of time and space.

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## PALEOGENE TROPICAL PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY AND MAGNETOBIOCHRONOLOGY

W.A. Berggren and Kenneth G. Miller

Confusion has arisen over the connotation and correlation of two competing tropical-subtropical Paleogene planktonic foraminiferal zonations (Berggren, 1969; Blow, 1979). This derives from the fact that the former scheme, when originally published, was viewed as provisional and precise definitions were not given for the zonal system. We review here the development of these two zonal schemes in a historical context, present a definition, in part revised and updated, of the P-zonation system of Berggren (1969), and correlate this and related zonal schemes to a magnetostratigraphic and ultimately, magnetobiochronologic framework to the extent possible.

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WHOI Contribution No. 6605.

## CENOZOIC FORAMINIFERAL BIOSTRATIGRAPHY OF THE CENTRAL NORTH SEA

F.M. Gradstein, M.A. Kaminski and W.A. Berggren

The Tertiary Grabens of the Central North Sea served as a link between the expanding Norwegian-Greenland Sea and the shallow epicontinental seas of Northwest Europe. We are studying the Tertiary shelly microfossil assemblages of the Central North Sea as part of a long-term investigation to further our understanding of the taxonomy, geographic distribution and paleoecology of agglutinated foraminifera as well as their utility for stratigraphy.

Following the widespread deposition of Danian chalk, south of about 60°N, the North Sea Basin underwent rapid subsidence (Sclater & Christie, 1980; Gradstein & Berggren, 1981; Wood, 1981). As a result, terrigenous clastic sediments in excess of 3 km thick accumulated in the central portion of the basin. Thickest sediments are found in the Central Graben, whereas the Viking Graven received between 2 and 3 km of sediment. Mudstones predominate, with deep marine clastic fans, like those of the Forties and Frigg oil fields developing during the early stage of Tertiary subsidence. In the Ekofisk area post-Danian olistostromes occur. By middle Miocene time the North Sea trough had been filled, leaving a neritic environment with a predominantly calcareous benthic microfauna dominated by Cassidulina, Elphidium, Fursenkoina, and Cibicidoides.

The post-Danian, Paleocene through early-middle Miocene mudstones harbour a rich and diversified flysch-type agglutinated benthic fauna (Gradstein and Berggren, 1981). In this study we report on the stratigraphic distribution of the benthic fauna in 29 exploratory wells. Over 2000 cuttings, sidewall cores and some core samples were analyzed (Table 1; Figure 1). In order to standardize the taxonomic nomenclature, all well samples were investigated by the senior author; assistance was provided by the junior authors on this project. A large collection of North Sea type specimen, housed with the senior author is available for comparative studies. The taxonomy of the benthic foraminifera follows Gradstein and Agterberg (1982), Gradstein and Berggren (1981) and Kaminski et al. (this volume). A revision of the taxonomy of the agglutinated morphotypes encountered is in progress and will be reported on elsewhere. The final stratigraphic analysis presented here involves the disappearance levels (tops) of 147 benthics, including over 60 agglutinated ones and some planktonic taxa.

For the purpose of this study the microfossil distribution data were augmented by the relative position in the wells (in feet or meters of depth below the rotary table) of physical log markers A through G as defined by A.C. Morton and R.B. Knox (personal communication, 1984).

In press: Proc. of 2nd Int. Workshop on Agglutinated Foraminifera.

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WHOI Contribution No. 6467.

## PLIOCENE-PLEISTOCENE RADIOLARIAN EVENTS AND MAGNETOSTRATIGRAPHIC CALIBRATIONS FOR THE TROPICAL INDIAN OCEAN

David A. Johnson, David A. Schneider, Dennis V. Kent, Catherine A. Nigrini and Jean Pierre Caulet

A composite of four piston cores from the Central Indian Basin and adjacent Ninetyeast Ridge has yielded a continuous magnetobiostratigraphic reference section for the most of the Pliocene and the Pleistocene (0.0-4.5 Ma). We identified thirty-three radiolarian events (first- or last- occurrences), and precisely correlated each event to the Neogene geomagnetic polarity time scale. Thirteen of these events are based on revised taxonomic studies of the genera Anthocyrtidium and Pterocorys. Some events show significant departures from synchroneity: five of the radiolarian first-appearances and seven of the last-appearances are time-transgressive by 0.4 m.y. or greater. We have proposed a revised, eleven-fold radiolarian zonation for the Pliocene-Pleistocene, using zonal boundaries defined by events which are easily recognized and are demonstrably synchronous in the tropical Indo-Pacific. The sequence of faunal and floral events reported in this paper will allow high-resolution biostratigraphic correlations within the tropical Indian Ocean; however, the same sequence of events is not necessarily applicable to other tropical or extratropical regions.

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WHOI Contribution No. 6687.

## NEOGENE BENTHIC FORAMINIFERAL STRATIGRAPHY AND DEEP WATER HISTORY OF SITES 645, 646 AND 647, BAFFIN BAY AND LABRADOR SEA

M.A. Kaminski, F.M. Gradstein, D.B. Scott and K.D. Mackinnon

Benthic foraminifers were examined from Neogene sediments of ODP Sites 645, 646 and 647 to determine first-order patterns in stratigraphy and to help constrain the paleoceanographic history of Baffin Bay, Eirik Ridge and the Gloria Drift.

Above a barren interval at Site 645, a Pleistocene Stetsonia assemblage displays affinity to the present-day deep Arctic Ocean, but an overlying Epistominella takayanagii assemblage has no modern analog. Miocene assemblages below a barren interval display low diversity and consist mainly of agglutinated species.

Site 646 recovered a Miocene Nuttalides umbonifera assemblage below seismic horizon "R3), and an agglutinated assemblage with "NADW-type" calcareous benthics above. The faunal turnover at seismic horizon "R3" reflects the onset of significant Denmark Straits overflow at 7.5 Ma. Agglutinated species disappear near reflector "R2", indicating a change in deep water properties associated with the re-opening of the Mediterranean and the onset of drift sedimentation at the Eirik Ridge at ~5.0 Ma. Drift formation ceased at ~2.5 Ma, concomitant with the appearance of ice-rafted sediments.

Site 647 is the only site in the Leg 105 transect that contains N. umbonifera assemblages of Pleistocene age, indicating a continued influence of southern-source bottom water at the Gloria Drift.

In press: Initial Reports of the Ocean Drilling Program, Leg 105, Vol. B.

WHOI Contribution No. 6525.

## Bolboforma FROM ODP LEG 105, LABRADOR SEA AND BAFFIN BAY AND THE CHRONOSTRATIGRAPHY OF Bolboforma IN THE NORTH ATLANTIC

Amy Pallant and Mike Kaminski

The genus Bolboforma, first described by Daniels and Speigler (1974) is a problematic group of calcareous microfossils. Bolboforma is most probably a planktonic cyst (Rogl and Hochuli, 1976) having protozoan or algal affinities (Poag and Karowe, 1986). Its known distribution at present suggests that various species may have potential for becoming increasingly good stratigraphic indicators. Bolboforma may become useful in areas where other calcareous planktonic microfossils are poorly preserved, for example the North Sea, the Norwegian-Greenland Sea and Baffin Bay. The purpose of this report is to summarize the known occurrences of Bolboforma in the North Atlantic and correlate them with a standard geochronology (Berggren et al., 1985 a,b). In addition, further observations of Bolboforma are reported from Sites 645, 646 and 647 (fig. 1).

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## PALEOGENE BENTHIC FORAMINIFERAL STRATIGRAPHY AND PALEOCOLOGY AT SITE 647, SOUTHERN LABRADOR SEA

Michael A. Kaminski, Felix M. Gradstein and William A. Berggren

Benthis foraminifers were examined from the Paleogene of ODP Site 647 and DSDP Site 112 in the Southern Labrador Sea. The Paleogene sequence of the deep Labrador Sea can be subdivided into 7 assemblages based on the ranges and relative abundance of characteristic taxa. The first occurrences (FO's) and last occurrences (LO's) of important benthic taxa are calibrated to a standard biochronology, by interpolating from our age model for Site 647. The stratigraphy of Site 647 is used to improve the age estimates of Site 112 cores. Fifteen microfossil events in Site 647 are also found in the sedimentary wedge along the Labrador Margin. A comparison of the probabilistic microfossil sequence from the Labrador Margin with Site 647 yields four isochronous benthic foraminiferal LO's. Two new species are described from Sites 647 and 112: Hyperammina kenmilleri, Kaminski n.sp., and Ammodiscus nagyi, Kaminski n.sp.

Significant faunal turnovers are observed at the Ypresian/Lutetian and Eocene/Oligocene boundaries. The Ypresian/Lutetian boundary is characterized by a Glomospira-facies, and is attributed to a rise in the lysocline associated with the NP14 sealevel lowstand. The Eocene/Oligocene boundary is delimited by the last occurrence of Spiroplectammina spectabilis and Reticulophragmium amplectens. The change from an Eocene agglutinated assemblage to a predominantly calcareous assemblage in the early Oligocene took place gradually, over a period of about 4 m.y., but the rate of change accelerated near the boundary. This faunal turnover is attributed to changes in the preservation of agglutinated foraminifers, since delicate species disappear first. Increasingly poorer preservation of agglutinated foraminifers in the late Eocene to earliest Oligocene reflects the first appearance of cool, nutrient-poor deep water in the southern Labrador Sea. The approximately coeval disappearance of agglutinated assemblages along the Labrador Margin was caused by a regional trend from slope to shelf environments, accentuated by the "mid"-Oligocene sealevel lowstand.

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WHOI Contribution No. 6548.

## PALEOCENE BENTHIC FORAMINIFERA OF TUNISIA A QUANTITATIVE ANALYSIS OF PALEOCENE BENTHIC FORAMINIFERAL ASSEMBLAGES IN CENTRAL TUNISIA

Pierre Saint-Marc and William A. Berggren

Correspondence analysis on Paleocene benthic foraminiferal data from eight outcrop sections in central and south Tunisia reveals four paleobathymetrically related assemblages which can be spatially and temporally distinguished: 1) a coastal assemblage with Anomalinoides umbonifera; 2) an inner shelf assemblage with lenticulinids and Haplophragmoides of the excavata-walteri group; 3) a "Midway-type" assemblage (mid to outer shelf) assemblage with Cibicidoides alleni and Osangularia plummerae; and 4) a "Velasco-type" assemblage (outer shelf to slope) with Nuttallides truempyi and Gavellinella beccariiformis.

The faunal succession indicates a general two-fold transgressive sequence separated by a distinct regression (eustatic-sea level fall) between the Danian and Thanetian (= Zones P 2/ P 3 boundary) and another regression in the late Paleocene. A general correlation is made with the current revision of the Exxon global sea level cycle chart.

In press: Journal of Foraminiferal Research.

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WHOI Contribution No. 6583.

# P E T R O L O G Y

## EXPERIMENTAL PETROLOGY OF NORMAL MORB NEAR THE KANE FRACTURE ZONE, 22-25°N, MID-ATLANTIC RIDGE

D. R. Tormey, T. L. Grove and W. B. Bryan

Melting experiments carried out at 1-atm and at 2 bar on mid-ocean ridge basalts dredged from the mid Atlantic ridge near the Kane Fracture Zone (KFZ, 22° to 24°N latitude) provide a basis for evaluating the role of crystal fractionation in generating compositional variability observed in "normal" mid-ocean ridge basalt.

The 1-atm olivine-plagioclase-clinopyroxene saturation boundary for KFZ lavas defines a path in mineral projection schemes and in oxide-oxide diagrams that is displaced from the same experimentally determined boundaries in FAMOUS (Grove and Bryan, 1983) and Oceanographer Fracture Zone (Walker et al., 1979) basalts. An important signature of low pressure differentiation is recorded in the quenched glass margins of moderately phyric KFZ lavas compared to their bulk rock compositions. The glass margins of sparsely phyric lavas record much smaller amounts of near surface, low pressure fractional crystallization, and their glass and bulk rock compositions are similar. In other chill margins the glass has evolved along low-pressure fractionation paths that are similar to those produced in the 1-atm experiments. Many of the lavas have retained phenocrysts in equilibrium proportions, so that their bulk rock compositions represent liquid compositions. When the effects of near-surface differentiation and crystal accumulation are removed from the Kane data set, and only liquid compositions are considered, a suite of basalt magmas can be identified that forms a trend in mineral component projection schemes parallel to the 1-atm oliv-plag-cpx multiple saturation boundary. These basalts have only olivine and plagioclase as phenocrysts and are well removed from clinopyroxene saturation at low pressure. Their compositional variation can not be generated by mixing any primary liquid composition with a low pressure liquid that has evolved along the oliv-plag-cpx multiple saturation boundary. Major and trace element models of this trend using olivine, plagioclase and clinopyroxene as fractionating phases match the compositional variability. This compositional trend is generated by fractionation at pressures greater than 2 bar, but within the plagioclase stability field. A review of the data for other normal MORB suites from this part of the mid-Atlantic ridge reveals a similar elevated pressure fractionation signature which persists when the effects of low pressure magma mixing are removed from the data set.

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## S E D I M E N T O L O G Y

### SEASONAL CYCLICITY OF LITHOGENIC PARTICLE FLUXES AT A SOUTHERN BLACK SEA SEDIMENT TRAP STATION

S. Honjo and the
International Black Sea Research Group

The annual particle fluxes were measured continuously for two and a half years at approximately two-week intervals at a Black Sea station 40 km from shore by two sediment traps moored 250 m and 1,200 m below the surface. There were three factors controlling the quality and quantity of particle flux at this station: 1) photosynthetic production of mineralized particles, 2) detrital input from Anatolian rivers, and 3) shelf sediments which were resuspended and transported off shore. The major component of the biogenic flux was coccoliths which were formed and settled during June to October. The characteristics of particles settled during this stage were similar to those of the light-colored laminae in the varved bottom sediments. The 1,200 m trap at this station, relatively near shore, received significantly larger lithogenic fluxes than did the 250 m trap, suggesting that the majority of the detritus was transported off shore in the water columns beneath the anaerobic interface. The lithogenic particles were settled in the winter by river transport and storm-induced resuspension of shelf sediments. The dark laminae, rich in clay, appeared to be formed thus during the winter period. The sinking speed of particles during the winter were estimated at about 125 (±60) meters per day, from observing the off-set of arrival times between the two traps. During the summer the settling rate of particles was slower than in the winter.

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WHOI Contribution No. 6428.

### PARTICLE FLUXES IN THE CENTRAL WEDDELL SEA; SEASONALITY AND ITS RELATIONSHIP TO ICE-EDGE DEVELOPMENT

Susumu Honjo, Dorinda Ostermann, Gerold Wefer, Gerhard Fischer and Dieter Fuetterer

Biogenic particle flux in the mid-

water column is primarily controlled by the balance between primary production and its consumption by zooplankton. In the Weddell Sea, primary production is influenced by a bi-annual solar cycle and by the large oscillation of the ice-edge throughout its open ocean area. In fact, the Weddell Sea is characterized by the largest ice coverage with the largest annual transgression of any area on earth (Zwally et al., 1983); this results in ecodynamic processes affecting roduction and transportation of particulate matter which differ greatly from those of other world oceans. In order to clarify the flux, origin, and mode of the vertical transport of oceanic particles in the pelagic Weddell Sea, we deployed a multi-year sediment trap experiment beginning in January, 1985. This is the initial report of this continuing German/US joint program.

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WHOI Contribution No. 6685.

## ANNUAL PARTICLE FLUX AND A WINTER OUTBURST OF SEDIMENTATION IN THE NORTHERN NORWEGIAN SEA

Susumu Honjo and Steven J. Manganini

In order to investigate year-round particle flux and its seasonal variability at a deep layer of high latitudinal open ocean, a time-series sediment trap was deployed at 458 m above the sea floor in water 2,123m deep at a station located at 75°51N, 11°28E, southwest of Spitsbergen. We collected twelve samples, each representing the particle flux for one month. This station was positioned at the northernmost extension of the Norwegian Current and was not covered by sea-ice throughout the year of the experiment. The annual particle flux was measured at 28.3 $gm^{-2}$, of which 49% was biogenic and 61% was lithogenic particles. The annual fluxes of organic carbon, calcium carbonate, and biogenic opal were 2.85, 6.61, and 1.96 $gm^{-2}$, respectively. There were three distinct seasonality phases in sedimentation: Phase 1, May to July was a period of relatively small flux reflecting the spring bloom material in the surface layer; Phase 2, August to November, was represented by the largest flux of carbon and other biogenic particles of the three phases; and Phase 3, December to May, was a period of outburst of lithogenic particle sedimentation which peaked during mid-January to mid-February.

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WHOI Contribution No. 6623.

## SEASONALITY OF OCEANIC PARTICLE FLUXES IN THE LOFOTEN BASIN, NORDIC SEA

S. Honjo, S.J. Manganini, V.L. Asper, G. Wefer and J. Thiede

The total annual particle flux was 22.8 $gm^{-2}$ from August, 1983 to August, 1984 measured by a deployed year-round time-series sediment trap experiment at a deep ocean station in the Lofoten Basin. Carbonate and opal occupied about 50% and 5%, respectively, while about 30% of the flux was composed of lithogenic particles. We found three sedimentary phases in each year; Phase 1: May to July, represented by a high flux content of diatoms and coccolithophores; Phase 2: August to November when the large flux had a high content of organic matter with abundant zooplankton remains and distinctly more aggregation of particles; Phase 3: December to April characterized by extremely small particle fluxes. The annual organic carbon supply was 1.4 $gm^{-2}$.

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WHOI Contribution No. 6451.

## RELATIONSHIP BETWEEN GRAIN DENSITY AND BIOGENIC OPAL IN SEDIMENTS FROM SITES 658 AND 660

Jürgen Mienert, Rudiger Stein, Peter Schultheiss and Shipboard Scientific Party

At Site 658, and especially at Site 660, sediments rich in biogenic opal were recovered. The fractions of biogenic silica, biogenic carbonate, and terrigenous material vary throughout the entire sequence at these sites (see chapters for Sites 658 and 660, this volume).

At Site 660, biogenic-opal contents up to 100% are common in Eocene sediments. In studying these opal-rich sediments, a rapid method for estimating biogenic opal published by Mann and Müller (1980) was found useful. These authors applied an x-ray method which measures the height of a broad, diffuse reflection band of opal extending from about 15° to 32° 2θ, with a maximum at about 22° 2θ (i.e., 4.04A) (Fig. 1, 1B).

Furthermore, this paper describes another method for estimating variations in the biogenic-opal content by using grain density. Grain density ($\rho$) can easily be determined by measuring the weight (G) and the volume (V) of the dry sediment, where $\rho = G/V(g/cm^3)$.

In press: Initial Reports of the Ocean Drilling Program.

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WHOI Contribution No. 6153.

## MAN'S INFLUENCE ON THE EROSION AND TRANSPORT OF SEDIMENT BY ASIAN RIVERS: THE YELLOW RIVER (HUANGHE) EXAMPLE

John D. Milliman, Qin Yun-shan, Ren Mei-e and Yoshiki Saito

During the Holocene sediment input from the Yellow River to the Yellow Sea and adjacent areas has amounted to about 3000 $km^3$. Detailed records from river gauging stations over the past 70 years, together with estimates based on earlier historic records, suggest that the river has contributed 2300 $km^3$ of sediment during the last 2300 years, an average discharge of 1 $km^3/yr$ (1 x $10^9$ t/yr). Prior to extensive agricultural use of the loess plateau in northern China (beginning about 200 BC), therefore, the river's load must have been about 0.1 $km^3/yr$, an order of magnitude lower than that at present. A broad delta 20 m below sea level suggests that early Holocene rates were higher than the preagricultural average and therefore that middle Holocene loads were lower.

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WHOI Contribution No. 6442.

## THE FECAL PELLET FRACTION OF BIOGEOCHEMICAL PARTICLE FLUXES TO THE DEEP-SEA

C. H. Pilskaln and S. Honjo

Fecal pellets produced by suspension-feeding crustacean zooplankton, specifically copepods and euphausids, have frequently been cited as in important mode of large particle transport in the open ocean. The objectives of the present study were to determine the various biogeochemical fluxes provided by pelagic crustacean fecal pellets, examine such fluxes as a function of variable levels of surface water productivity and depth, and assess the overall fecal pellet contribution to oceanic particle fluxes as measured with sediment traps.

Pellet subsamples were obtained from particulate samples collected at depths between 389 and 5068 m by moored PARFLUX sediment traps deployed for up to 12 months at three tropical-subtropical open-ocean localities. The sites were located over the East Hawaii Abyssal Plain (P site), the Demerara Abyssal Plain (E site), and in the Pacific Panama Basin (PB site).

Fecal pellet flux and chemical composition were found to vary significantly on a geographic scale as a function of productivity levels in the surface waters. The total carbonate, organic carbon, opaline silica, and lithogenic fluxes provided by pellets at the oligotrophic $P_1$ site were one to two orders of magnitude less than that measured at the eutrophic station in Panama Basin. The pellet data show that contrary to previous assumptions, these biogenic aggregates are responsible for no more than 5% of the total mass flux of oceanic particulate material. Despite the fact that at all trap depths, large numbers of intact pellets were collected which displayed minimal effects of dissolution and microbial degradation, fecal pellets contributed an average of only 1-10%, 0.5-5%, 1-3%, and 0.5-4% to the total measured mass fluxes of organic, carbonate, opaline silica, and lithogenic material, respectively. However, the pellets showed elevated $^C/N$ ratios (9-14) as well as high organic content (representing up to 50% of the individual pellet weight), suggesting that they constitute an important source of organic carbon for the deep-sea benthos. Rapid remineralization of the organic-rich pellets must occur at the deep-sea sediment/water interface as these biogenic aggregate were completely absent from all site core tops.

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WHOI Contribution No. 6406.

## BEACH MORPHOLOGY OBSERVATIONS DURING NSTS

Richard J. Seymour and David G. Aubrey

Changes in beach morphology were recorded during all of the field experiments in Nearshore Sediment Transport Study (NSTS) to provide baseline data for dynamical observations as well as to study cross-shore transport effects. Measurements were made with both conventional techniques (rod-and-level wading surveys and boat surveys with a sonic depth finder) and with two experimental profilers, yielding four data sets. The beach profiles, as well as pertinent wave and tide parameters, were reported in Seymour (1986). This paper will focus on the findings of these studies with some additional comments on the performance of the experimental profiling methods.

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WHOI Contribution No. 6436.

## SEDIMENT DISTRIBUTION AND SEA FLOOR MORPHOLOGY OF STORBANKEN: IMPLICATIONS FOR THE GLACIAL HISTORY OF THE NORTHERN BARENTS SEA

Andaers Solheim, John D. Milliman and Anders Elverhφi

Acoustical (sparker, 3.5 kHz and side scan sonar) and sedimentological data from a local study on Storbanken in the northern Barents Sea support the concept of a Late Weichselian ice sheet covering most of the Barents Sea. During a major halt in the retreat of the ice sheet, locally thicker (38 m) accumulations of ice proximal glaciomarine sediments were deposited, after which rapid retreat took place. Sea floor morphology indicates that the retreat across Storbanken most likely took place without surging or climatically controlled oscillations.

Intense iceberg ploughing characterizes the sea floor down to 210-210 m waterdepth. Most of this is relict, but occasional gouges in the shallowest regions may have had a more recent origin. The apparent lower limit of ploughing, interpreted in terms of relative sea level, indicates a rather moderate isostatic depression. This probably results from a thin ice sheet, fed from several ice source areas. Depth of the plough marks is largely dependent on thickness of the glaciomarine sediments. A thin and patchy layer of overcompacted till fills local depressions in the sedimentary bedrock surface and forms a flat base for iceberg ploughing.

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WHOI Contribution No. 6506.

## RADIOLARIAN FLUX AND SEASONALITY: CLIMATIC AND EL NINO RESPONSE IN THE SUBARCTIC PACIFIC, 1982 - 1984

Kozo Takahashi

Seasonal flux distributions of numerically dominant radiolarian species were studied using PARFLUX 1982-1984 high resolution, time-series sediment trap samples recovered from the eastern subarctic Pacific Station PAPA (water depth: 4,200 m) in the Gulf of Alaska. Flux patterns of several major radiolarian species showed more temporally confined seasonal maxima than those of siliceous phytoplankton groups, suggesting more important seasonal flux signals than those of siliceous phytoplankton. These species showed significant flux reduction from year 1 to year 2 associated with an El Nino event, as did siliceous phytoplankton. On the other hand, fluxes of three radiolarian subgroups, and some other radiolarian species showed little change in timing or amplitude of seasonal patterns from year 1 to year 2 except for the presence/absence of a summer maxima. This type of radiolarian flux signal is a reflection of recurring large changes in seasonal environmental conditions and, to a lesser extent, of response to the deviations of interannual amplitudes. Two generic pairs of radiolarian fluxes showed clear temporal niches which may have evolved due to dietary preferences. Biological competition may take place among species from different genera but not within a genus. Fluxes of juvenile and adult forms of two Pterocanium species were compared in order to understand their reproductive cycles. Reproduction appears to occur sporadically throughout most of the year and non-synchronously among population members. The longevity of Pterocanium species was estimated to be several weeks. There are two separate radiolarian sinking processes; accelerated sinking via aggregates and discrete sinking. Smaller sized species tend to sink faster than larger ones due to aggregate incorporation. Radiolarians are considered a good measure of productivity. The contribution of

Phaeodarians can be as high as 10% or more in total opal flux. Large-sized phaeodarian specimens are involved in this high percentage and play a significant role in silica redistribution since they dissolve quickly.

In press: Global Biogeochemical Cycles.

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WHOI Contribution No. 6466.

## RESPONSE OF SUBARCTIC PACIFIC DIATOM FLUXES TO THE 1982-1983 EL NINO DISTURBANCE

Kozo Takahashi

Time-series sediment trap samples were collected during October 1983 - August 1984 at 3800 m at Station PAPA (50°N, 145°W; water depth: 4200 m) in the northeastern North Pacific. Components of diatom fluxes have been measured and compiled with 1982-83 records. Most diatom species showed significantly lower cumulative fluxes in the second year than in the first. Second year seasonal flux patterns were also notably different from those in the first year. Many of the differences are attributed to the second year's change in density structure in the upper 100 meters, resulting in a poor nutrient supply to the euphotic layer. The changes in the density structure was caused by the 1982-1983 El Nino. The El Nino effect was analogous to notable changes in hydrography and biota reported elsewhere in the eastern subarctic Pacific.

Diatom fluxes clearly respond to this unusual climate change as well as to normal seasonal changes. The percentages of each species within total centric diatoms showed monotonous values throughout year 2 when productivity was generally low. The percent values were similar to those of year 1's low production period, indicating consistent low productivity signals. High diatom fluxes were accompanied by high percentages of Chaetoceros, suggesting high productivity signals. This strongly supports the contention that diatoms are sensitive environmental and climate indicators.

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## PLANKTONIC FORAMINIFERA PRODUCTION: SEASONAL AND INTERANNUAL CHANGES IN THE NORTH PACIFIC

Robert C. Thunnel and Susumu Honjo

It is well established that there are distinct seasonal cycles in the production of plankton, and that the nature of these cycles varies both geographically and in terms of phytoplankton-zooplankton coupling (1). Only recently have attempts been made to quantitatively measure seasonal variability in the flux of various biogenic components from the ocean surface to the sea-floor (2-5) and to relate this flux to local hydrographic conditions (6). A three year sediment trapping project in the subpolar North Pacific allows us to document both seasonal and interannual variability in the flux of planktonic foraminifera from the sea surface. A model based on the temperature preferences of planktonic foraminiferal species, thermal structure of the upper water column and food availability is proposed to explain the observed temporal changes in foraminiferal production and flux.

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# T E C H N I C A L  R E P O R T S

## KING'S BAY/CUMBERLAND SOUND, GEORGIA PART II: NUMERICAL MODELING

David G. Aubrey

As a complement to field measurements of waves, surface tides, currents, and sediment transport, numerical modeling of King's Bay/Cumberland Sound was initiated. Diagnostic numerical models (both 1- and 2-dimensional were applied to determine their applicability to estuaries of the same scale as King's Bay. One-dimensional models showed the estuarine system to be ebb-dominant, in accord with observations. This model did not reveal any extreme system sensitivity to changes in channel geometry on the scale expected from maintenance dredging. The two-dimensional model (a finite element model having a moving boundary formulation) was run to examine its applicability for diagnostic modeling of these systems. Preliminary

results indicate the method is promising, but some model developments are indicated. Suggested model developments include: semi-implicit algorithm to reduce run-time; mass-conserving boundary conditions at tidal boundaries; implementation of a two-level momentum equation; algorithm development to extend the deforming element concept for smaller estuarine space scales; and formulation of a comprehensive interactive graphical package to facilitate model formulation, boundary and domain gridding, and presentation of results. This latter graphical task is essential for successful application of these numerical models. Results from these studies suggest that diagnostic models of shallow estuaries will be a valuable tool to be used in conjunction with more expensive "predictive" models, to understand circulation and transport processes under natural and impacted conditions.

Supported by: Naval Facilities Command through the Naval Civil Engineering Laboratory and partial support from WHOI Coastal Research Center.

WHOI Technical Report 87-2 (CRC-87-1).

## THE TECTONICS AND THREE-DIMENSIONAL CRUSTAL STRUCTURE OF SPREADING CENTERS: MICROEARTHQUAKE STUDIES AND TOMOGRAPHIC INVERSION

Douglas R. Toomey

Two-thirds of the Earth's surface has been formed along a global system of spreading centers that are presently manifested in several different structural forms, including the classic rift valley of the Mid-Atlantic Ridge, the more morphologically subdued East Pacific Rise, and the pronounced en echelon structure of the Reykjanes Peninsula within southwestern Iceland. In this thesis, each of these different spreading centers is investigated with microearthquake studies or tomographic inversion of travel times. Results of these studies are used to constrain the spatial variability of physical properties and processes beneath the axis of spreading and, together with other observations, the temporal characteristics of crustal accretion and rifting.

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## GEOTHERMAL HEAT FLUX AT THE COST B-2 AND B-3 WELLS, U.S. ATLANTIC CONTINENTAL MARGIN

B. Della Vedova and R.P. Von Herzen

Heat flow estimates at two sites on the U.S. Atlantic continental margin are presented. An estimate of the heat flowing from the basement also has been obtained. About 4.8 km of sediments penetrated at the COST B-2 and 4.0 km at the COST B-3 were deposited since the Upper Jurassic. Well logs were used to evaluate thermal gradients and sedimentation rates, whereas thermal conductivities and radiogenic heat productions were measured on drill cuttings samples.

A procedure to estimate in-situ thermal conductivity from drill cuttings and well logs is described. A substantial set of samples, in the form of drill cuttings, were sorted in four major lithologies: sandstones, siltstones, shales and limestones. Laboratory measurements of density, porosity, thermal conductivity, quartz (%), potassium (%), uranium (ppm) and thorium (ppm) were performed on 128 reorganized and pulverized samples. A significant correlation of the matrix thermal conductivity to quartz and potassium content was found. In situ porosity and volume fraction of each lithology, determined mainly from well logs, were used to calculate in situ mean thermal conductivity. Finally the mean in situ vertical component of the thermal conductivity, as required for heat flow values, has been estimated from a correction factor for the anisotropy of each lithology. The in-situ temperature and anisotropy effects substantially decrease estimates of thermal conductivity at depth.

Below the uppermost 1 km in both wells the best estimate of the thermal gradient is 26.3°C $km^{-1}$ at COST B-2 and 26.1°C $km^{-1}$ at COST B-3, whereas in situ mean thermal conductivities range between about 1.8 and 1.9 W $m^{-1}$ $K^{-1}$ (4.3-4.5 T.C.U.). The average heat flow is estimated as about 45 mWm$^{-2}$ (1.07 H.F.U.) at COST B-2 and 44 mWm$^{-2}$ (1.06 H.F.U.) at COST B-3, with an uncertainty of about 20-25%. The mean radiogenic production in sediments at the two sites has been estimated as 1.83 (COST B-2) and 1.44 (COST B-3) $10^{-6}$ $Wm^{-3}$. With a 12-14 km thick sedimentary sequence a radioactive contribution of 20-25 $mWm^{-2}$ can be expected.

The effects of sediment deposition, compaction, pore water advection and radiogenic heat production have been combined in a numerical model (Hutchison, 1985) to estimate the undisturbed basement heat flux. Although the sedimentation depresses the basement heat flux by 15-20%, this

effect is more than compensated by radioactive heat production in the sediments, so that the surface flux is estimated to be higher than that from the basement. The latter is calculated at about 33-39 $mWm^{-2}$ (0.8-0.9 H.F.U.), a relatively low value. The overall uncertainty is about 20-25%, and other estimates on continental margins with thick sediments (e.g. Reiter and Jessop, 1985) probably have at least a similar uncertainty.

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WHOI Technical Report 87-28.

## APPLICATION OF SEASAT ALTIMETRY TO TECTONIC STUDIES OF FRACTURE ZONES IN THE SOUTHERN OCEANS

Mavis Lynn Driscoll

Gravity derived from Seasat altimetry has provided a means of estimating seafloor topography and its compensation, which in turn can be used to understand the evolution of oceanic lithosphere. In the first study of this thesis, the correlation between the geoid, and seafloor topography is investigated along a section of the Southwest Indian Ridge. Geoid anomalies computed from a simple thermal model fairly accurately predict the intermediate-wavelength anomalies across the fracture zones. The shorter wavelength anomalies are consistent with those calculated from topography using elastic plate compensation. In the second study, fracture zones along the Southwest Indian Ridge are identified using altimeter profiles and bathymetry. Finite poles of rotation are determined from both the fracture zone locations and magnetic anomaly lineations for anomalies 6, 13, and 20. A present-day pole of rotation claculated from transform fault azimuths determined primarily from their geoid anomalies, agrees with published poles based on bathymetric data. In the third study, the rate of change of the geoid with age has been estimated as a function of age from geoid offsets across the Eltanin and Udintsev fracture zones and used to constrain thermal models of lithospheric cooling. Although the thermal plate cooling model is successful in predicting both seafloor depths and heat flow values out to ages of at least 80 m.y. B.P., it cannot explain the observed geoid slope values for these two fracture zones.

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WHOI Technical Report 87-23.

## TIDAL VELOCITY ASYMMETRIES AND BEDLOAD TRANSPORT IN SHALLOW EMBAYMENTS

Virginia A. Fry

Tidally forced circulation can cause a net near-bed transport of sediment when the tidal velocity is asymmetric about a zero mean (flood or ebb dominant) and the transport rate is nonlinearly related to velocity. The relationship between elevation and velocity is elucidated here to enable one to determine from tide gauge data and sediment transport relations whether tidals asymmetry may cause net sediment transport. Tidal elevation and tidal velocity are related through the equations of motion of the fluid. If the estuary is shallow, the change in cross-sectional area of the channel with the tide is significant with respect to total area: the equations become nonlinear and an exact solution does not exist. A relationship between elevation and velocity in a non-linear system is derived through the continuity equation and shown to be significantly different than the linear relation. Finite difference numerical solutions of the one-dimensional, shallow water non-linear equations are compared to the continuity relation and are in good agreement.

The relationship between elevation asymmetry and ratio of flood-to-ebb bedload transport is calculated for both the linear relation between elevation and velocity and the nonlinear relation. Results show that the ratio of flood-to-ebb bedload transport as calculated from the nonlinear relation between elevation and velocity is similar to the flood-to-ebb ratio calculated from the linear relation.

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WHOI Technical Report 87-51.

## PARTICLE FLUX IN THE WESTERN BLACK SEA IN THE PRESENT AND OVER THE LAST 5,000 YEARS: TEMPORAL VARIABILITY, SOURCES, TRANSPORT MECHANISMS

Bernward J. Hay

The particle flux in the present and over the last 5,000 years was investigated in the western Black Sea in a comparative study with samples from time-series sediment traps and laminated core sediments. The particle flux varies considerably seasonally and regionally. Dominant particle sources are biogenic and terrigenous matter. The relative importance in the particle supply varies seasonally and can be grouped into three phases: Phase I (June-October; coccolithophorid production), Phase II (November-January; resuspension of shelf deposits), and Phase III (February-May; river input of terrigenous matter and diatom production).

Throughout the last 1,000 years, the particle flux was more than 5 times larger in the western Black Sea compared to the southwestern Black Sea, mostly because of the 11 times larger supply of coccoliths. The coccoliths were probably largely produced on or adjacent to the Danube fan and subsequently resuspended and transported offshelf by fall storms. White laminae contain over 90% coccoliths and, using the trap samples as a standard, are possibly deposited between about June and January; black laminae contain largely terrigenous matter and form during the peak river discharge period between about February and May. Compared to the last 1,000 years, the particle flux between 1,000 and 5,000 years B.P. was smaller by a factor of 3.

Seasonally, the terrigenous matter from the Danube appears to be traceable in the southwestern Black Sea, as seen by the Ti/Al and illite/montmorillonite ratios in the sediment trap samples.

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WHOI Technical Report 87-44.

## CURRENT MEASUREMENTS FROM THE NORTHERN NORDIC SEAS 1983-1986

Susumu Honjo, Christine M. Wooding and Gerold Wefer

Records from ten Aanderaa current meters deployed along with 5 current meter/sediment trap mooring arrays in the Fram Strait and Greenland Basin, each deployed for approximately one year between 1983 and 1986, are presented in this data file. Data included are current vectors, temperatures, frequency spectra, and two- and three-dimensional vector diagrams.

Supported by: ONR Contract N00014-85-C-0001.

WHOI Technical Report 87-18.

## PARTICLE FLUXES, NORTH-EASTERN NORDIC SEAS: 1983-1986 (NORDIC SEAS SEDIMENTATION DATA FILE, VOL. 1)

Susumu Honjo, Steven J. Manganini, Amy Karowe and Bonnie L. Woodward

Seventy-nine particle flux samples were collected from 1983 to 1986 using 7 automated time-series sediment traps at 6 stations distributed in the northern and eastern portion of the Nordic Seas as part of a German/U.S. joint program on arctic sedimentation studies. Each sample represents either one month or two weeks of sedimentation at approximately 400 m above the sea floor. In this data file the results of laboratory analysis conducted at the Woods Hole Oceanographic Institution, U.S.A. of the main sedimentological criteria: total mass, carbonate, opal, combustible, organic carbon, nitrogen, and lithogenic mass are presented in both tabular and histogram form. Results from the southern and western portion of the Nordic Seas will be published as they become available.

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WHOI Technical Report 87-17.

## BLACK SEA SEDIMENTATION DATA FILE, VOL. 1 PARTICLE FLUXES, SOUTH CENTRAL BLACK SEA: 1982-1985

Susumu Honjo, Steven J. Manganini, Vernon L. Asper, Bernward J. Hay and Amy Karowe

Annual particle fluxes were measured by sediment traps deployed at a station about 40 km north of Amasra, Southern Black Sea, by an international team of oceanographers from Germany, Turkey, and the United States. This experiment continuously monitored oceanic particle flux for two and a half years from October 28, 1982 to April 6, 1985 at approximately two-week intervals at 250 m and 1200 m below the surface using 1.2 $m^2$ Mark 5-12 time-series sediment traps. The water depth at this station was about 2,200 m and both traps were situated within the anoxic layer of the Black Sea. The collected flux samples were analyzed at the Woods Hole Oceanographic Institution to document the basic sedimen-

tary characteristics using a quarter of each sample split. In the first data file from this experiment, total mass, carbonate, noncombustible, combustible, opal (biogenic silica), organic carbon, and organic nitrogen fluxes data are presented in bar graphs and detailed tables, in unit samples covering a two-week period at each depth. The Black Sea Sedimentation Data File is intended to provide source data on particle fluxes from this unique ocean environment for further investigation and for planning advanced research programs.

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WHOI Technical Report 87-25.

## MEASURE: A PROGRAM FOR MORPHOMETRIC MEASUREMENTS

David Lazarus

'MEASURE', a FORTRAN77 program for collecting morphometric measurements, has been developed. Features of the program include the ability to accept distance and outline measurements in either 2 or 3 dimensions, to collect several different types of measurements on individual specimens, and to keep a running tally of the number of each type of specimen measured. The current version of the program is used for taxonomic and evolutionary studies of radiolarian microfossils and accepts data input from a digitizer tablet and a vertical measurement device attached to a microscope. An ordinary text file is used to configure the program for any desired set of distance or outline measurements. The program is highly modular, and is relatively easy to expand and modify. This report provides a detailed description of the program for both end-users and for programmers wishing to adapt MEASURE to their own uses. A full listing of the source code is included.

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WHOI Technical Report 86-40.

## A DATA-BASE OF ANTARCTIC PRE-PLEISTOCENE SEDIMENT CORES

David Lazarus, Amy Pallant and James D. Hayes

A listing of high southern latitude (>30°S) pre-Pleistocene sediment cores is given for samples obtained by the coring and drilling programs of the Lamont-Doherty Geological Observatory, the Antarctic Program of the Florida State University, the French Museum national d'Histoire naturelle, and the Deep Sea Drilling Program. Information on geologic age, core length, lithology, bathymetry, and geographic location are given for each sediment sample. Ages of cores are given whenever possible to the nearest sub-epoch (middle Miocene, etc.), together with (when known) the fossils used to determine the age, and the source of the age determination. Many core ages are from previously unpublished sources. The listing provides information on approximately 500 different cores. A computer-searchable version of the database may be obtained by writing to the senior author.

A brief analysis of latitudinal and bathymetric patterns of sedimentation is also given for the Paleogene, Miocene, and Pliocene of the Southern Ocean. Throughout the Neogene, an essentially modern pattern of sedimentation is seen, with carbonate ooze predominating north of the present-day position of the polar front, siliceous ooze between the polar front and approximately 65°S, and clay near the Antarctic continent and in water depths >4 km. Paleogene and Cretaceous patterns of sedimentation appear to be different, but are difficult to distinguish due to plate motion and subsidence, and also because of the relatively small number of available pre-Neogene sediment cores.

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WHOI Technical Report 87-16.

## OPTIONS FOR RADIOACTIVE AND OTHER HAZARDOUS WASTE SITING WITHIN THE U.S. EXCLUSIVE ECONOMIC ZONE

Frank T. Manheim and Allyn Vine

Some areas of the E.E.Z. (Exclusive Economic Zone) offer technical, political and economic options that may complement existing approaches to hazardous waste storage and disposal.

Supported by: U.S. Geological Survey and WHOI Ocean Indsutry Program.

WHOI Technical Report 87-12.

## CHART
## A COMPUTER PLOTTING PACKAGE FOR THE DISPLAY OF POSITION-DEPENDENT MARINE DATA

Ann Martin

Computer program CHART produces plots

of navigation tracks and data points in a choice of 14 projections where navigation coordinates are defined. It was written specifically for the plotting and annotation of geological and geophysical data; however, any data which includes geographical coordinates can be plotted.

The package was designed for broad flexibility of applications and for ease of use. Parameters are entered interactively; the user responds to online prompts worded in plain English. Several levels of default choices are incorporated; a user who takes all defaults can produce a plot by entering only the data source and format, and plot bounds.

CHART can be used on any Digital Equipment Corporation VAX machine running VMS. It uses plotting subroutines (MAPPACK) maintained by the WHOI Information Processing & Communications Laboratory (IPCL) to draw projection grids and coastlines, and to locate the position for each data point. The program creates a file of Calcomp plotting instructions for subsequent plotting.

Some additional features of CHART: coastlines; multiple data sets on one grid; empty grid without data points; corner registration marks; calculation of plot size; user-defined input format; online entry of data points where large time gaps occur; online documentation.

Supported by: Sandia National Laboratories and WHOI Ocean Industry Program.

WHOI Technical Report 86-43.

## THE EFFECT OF A SHALLOW LOW VISCOSITY ZONE ON MANTLE FLOW AND ITS EXPRESSION AT THE SURFACE OF THE EARTH

Elizabeth M. Robinson

Many features of the oceanic plates cannot be explained by conductive cooling with age. A number of these anomalies require additional convective thermal sources at depths below the plate: midplate swells, the evolution of fracture zones, the mean depth and heat flow relationships with age and the observation of small scale (150-250km) geoid and topography anomalies in the Central Pacific and Indian oceans. Convective models are presented of the formation and evolution of these features. In particular, the effect of a shallow low viscosity layer in the uppermost mantle on mantle flow and its geoid, topography, gravity and heat flow expression is explored. A simple numerical model is employed of convection in a fluid which has a low viscosity layer lying between a rigid bed and a constant viscosity region. Finite element calculations have been used to determine the effects of (1) the viscosity contrast between the two fluid layers, (2) the thickness of the low viscosity zone, (3) the thickness of the conducting lid, and (4) the Rayleigh number of the fluid based on the viscosity of the lower layer.

Supported by: NASA-NAG Grant 5-415 and an NSF fellowship.

WHOI Technical Report 87-34.

## AMBIENT NOISE ANALYSIS AND FINITE DIFFERENCE MODELLING OF VLF BOREHOLE SEISMIC DATA

R.A. Stephen, S.A. Swift and S.T. Bolmer

This report describes a preliminary analysis of borehole seismic data to determine VLF/Sub-bottom Seismic Noise in the Atlantic and the preliminary results of finite difference modelling for a Cape Fear environment.

Noise levels were not a simple function of depth and there are indications that noise levels may depend on local geology about a given receiver position and/or on clamping. Coherency of the noise was generally poor ($<0.8$) and was independent of depth. There is no evidence for distinct polarizations or directionality of the noise. The lowest determined value for ambient noise power on the vertical component was $10^{-4}$ $nm^2/Hz$ in the frequency range from 5-50 Hz. The better clamped horizontal component had comparable power values. In conclusion, although the drill ship was on the site and drill pipe was in the hole, analysis of the data for a large number of windows can provide meaningful upper bounds on the ambient noise levels in the upper crust.

Supported by: ONR Contract N00014-87-K-0007.

WHOI Technical Memorandum 4-87.

## SHELLFISH DISEASES: CURRENT CONCERNS IN THE NORTHEAST

Alan W. White

This report is a summary of a workshop on shellfish disease issues of current concern to the shellfishing industry of the northeastern United States. The workshop, sponsored by the Woods Hole Oceanographic Institution Sea Grant Program, was held on February 26, 1987, at the Woods Hole Oceanographic Institution.

Its principal aim was to keep the shellfishing community abreast of the latest information on diseases of importance to wild and cultured shellfish stocks in the area. Topics addressed by invited speakers (scientists, managers, and growers) included 1) MSX oyster disease, which has recently caused a high incidence of oyster mortality at one location on Cape Cod, 2) tumors of soft-shell clams, 3) "brown tide", a new problem with recent dramatic effects on scallops in New York and mussels in Rhode Island, and 4) shellfish hatcheries and shellfish importation in relation to disease concerns. The workshop was attended by more than 100 people, primarily shell-fishermen, shellfish officers, members of town shellfish commissions, and shellfish biologists from Massachusetts.

Supported by: NOAA Sea Grant
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WHOI Technical Report 87-13.

# DEPARTMENT OF OCEAN ENGINEERING

Albert J. Williams III, Chairman

## FREQUENCY HOPPING PATTERNS FOR SIMULTANEOUS MULTIPLE-BEAM SONAR IMAGING

Philippe M. Cassereau and Jules S. Jaffe

This paper describes the design of frequency-hopped signals for a multi-beam imaging system. A frequency hopping pattern is a frequency-coded uniform pulse train. The signal is divided into M time intervals, with each interval assigned a different frequency chosen from a set of N frequencies. A set of N patterns composed of N - 1 frequencies can be generated using first-order Reed-Solomon codewords. These patterns exhibit very good correlation properties. In a frequency-hopped multi-beam imaging system, each beam is associated with a pattern and transmits a coded waveform. All N beams can be transmitted simultaneously resulting in a high scan-rate, high resolution imaging device. Furthermore, in the presence of noise and medium spreading effects, a frequency-hopped imaging device performs better than conventional systems by showing better noise rejection and less sensitivity to spreading effects.

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WHOI Contribution No. 6368.

## DEEPWATER SEDIMENT CONCENTRATION PROFILING IN HEBBLE USING A ONE MEGAHERTZ ACOUSTIC BACKSCATTER SYSTEM

James F. Lynch, Thomas F. Gross, Charles Libicki and Keith Bedford

As part of the High Energy Benthic Boundary Layer Experiment (HEBBLE), a one megahertz acoustic backscatter system (ABSS) was deployed in 4800m of water on the Nova Scotian continental rise. The purpose of the instrument was to non-intrusively measure a relative concentration vertical profile time series, which it did over the course of one year, from September 1985 to September 1986. In this paper, we discuss the details of the ABSS instrument, the preliminary results of the time series data analysis, the issues to be addressed in a more complete analysis, and the ramifications of the results on sediment transport modeling.

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WHOI Contribution No. 6398.

## MULTIMODE IMAGING FOR UNDERWATER ROBOTS

Jules S. Jaffe and Philippe M. Cassereau

In this paper we introduce a new application for ultrasonic imaging that has not received much publicity: ultrasonic imaging for underwater robots. After a brief survey of some of the applications we consider the conceptual design of an underwater ultrasonic imaging system. The goal of the system is to provide 3-dimensional images about objects that are distances of 10's of meters away at real time video rates. In order to achieve this goal, we suggest that a principle of spatially variant insonification (SVI) be employed. This technique propagates multiple sonar beams into the medium simultaneously and upon reception, the individual beams are separated. In order to accomplish this, each sonar beam uses a specific code. The mathematical properties of the specific code that are employed insure that this is possible. The design of these codes is identical to that encountered in multi-access, spread spectrum, communication systems. Therefore, the time-bandwidth properties of the system limit the simultaneous requirement of decorrelatable beams and good range resolution. As a specific implementation of the technique a frequency hopping code is presented. This code is then combined with a sparse receiving array. The resultant system satisfied the above criteria.

Presented at: SPIE International Symposium on Pattern Recognition and Acoustic Imaging, February 1987.

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WHOI Contribution No. 6415.

## HIGH PERFORMANCE SUPERVISORY CONTROL OF VEHICLES AND MANIPULATORS

Dana R. Yoerger and James B. Newman

In this paper, research and development leading to a supervisory control system for the JASON vehicle is described. The overall goal of the program is to make JASON more effective and easier to operate. The system will combine coordinated computer control of the vehicle and manipulator movements and a man-machine interface that helps the operator take advantage of the automated features.

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WHOI Contribution No. 6416.

## HIGH PERFORMANCE FREE-FALL PROFILING VEHICLES

Albert M. Bradley and Eileen Hofmann

Rising costs have forced the oceanographic community to consider more efficient methods for hydrographic studies. Global scale synoptic studies such as WOCE (World Ocean Circulation Experiment) accentuate the need for more efficient use of available ship time. A high performance profiler, the Flying Fish, is under development to meet this need. Designed at the Woods Hole Oceanographic Institution, The Flying Fish reduces the time required for a CTD (Conductivity, Temperature, Depth) profile from about four hours to thirty minutes. Comparisons between temperature and salinity profiles made with a prototype Flying fish and those obtained with a conventional wire lowered CTD are presented. Discussions of applications, instrument limitations and ideas for design improvements are discussed.

Published in: Marine Technology Society Journal, June '87, (21) 2, 33-41.

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WHOI Contribution No. 6427.

## TASK RESOLVED MOTION CONTROL OF VEHICLE-MANIPULATOR SYSTEMS

Dana R. Yoerger and
Jean-Jacques E. Slotine

Teleoperated vehicles and manipulators are employed routinely underwater and are being developed for use in space. This paper presents techniques that free the human operator from those elements of the motion specification task that do not actually require his skills and decisions, yielding improved performance and reduced operator workload. A model of the environment is employed to vary the reference frame for the operator's motion commands throughout the task. Through these techniques, the operator is provided with a set of coordinates that correspond naturally to the task, while the remaining degrees of freedom are controlled automatically. Finally, rule-based inverse kinematics algorithms are employed to permit constructive use of the kinematic redundancies typically found in vehicle manipulator systems.

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WHOI Contribution No. 6429.

## SUPERVISORY CONTROL ARCHITECTURE FOR UNDERWATER TELEOPERATION

Dana R. Yoerger and
Jean-Jacques E. Slotine

An overall concept and specific system elements for teleoperated vehicles and manipulators are presented. The approach emphasizes continuous, real-time sharing of control between both the human operator and the computer system and is intended for application to the JASON underwater vehicle now in development. As JASON will have extremely high communications bandwidth available through a fiber optic cable, the emphasis will be on aiding and extending the capabilities of the human operator. Specific elements presented include task-resolved motion specification, rule-based inverse kinematics, and robust and adaptive nonlinear tracking control.

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WHOI Contribution No. 6430.

## AN INVERSE KINEMATIC ALGORITHM FOR MANIPULATORS WITH REDUNDANT DEGREES OF FREEDOM

Jean-Jacques E. Slotine
and Dana R. Yoerger

The problem of selecting suitable inverse kinematics solutions for redundant manipulators naturally arises in a number of important applications, such as vehicle-manipulator system control. In this paper, the inverse kinematics solution for general manipulators is approached as a control problem with no uncertainty. A computa-

tional algorithm is proposed, which simulates the closed-loop behavior of a hypothetical manipulator of the same geometry as that of the manipulator of interest, but possessing simple known dynamics. This approach has several advantages: algorithm convergence and convergence rates can be guaranteed from Lyapunov stability analysis; the design can be guided by physical insight on the simulated manipulator behavior; the algorithm does not require any matrix inversion or pseudo-inversion, and therefore avoids the associated numerical unstabilities; finally, the particular kinematic solution can be shaped in a meaningful way, based again on the physical analogy. The approach is illustrated in simple examples.

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WHOI Contribution No. 6431.

## JASON JUNIOR'S CONTROL SYSTEM

James B. Newman

The ROV JASON Junior (JJ) is controlled by a computer inside the manned research submarine ALVIN. The computer receives commands from the operator handbox and data from sensors on the vehicle, transmits commands to the vehicle motors, and presents data on the operator's display. The short development time and the requirement for a dependable, turn-key computer led to a PC-based system which was easily supported but which in fact required no support while it was at sea.

This paper will describe the JJ computer, the interfaces to the vehicle and operator and the software that ran the system.

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## AN ARCTIC REMOTE AUTONOMOUS MEASUREMENT PLATFORM

Kenneth E. Prada, Donald E. Koelsch, Warren E. Witzell and Robin C. Singer

Perceptual ice cover in the Arctic inhibits broad analysis of the region. Ice camps and research ships do not provide sufficient coverage. Satellites expand the coverage, but only within the limits of onboard sensors. A multidisciplinary data collection tool is needed to expand coverage in ice covered regions.

The Arctic Remote Autonomous Measurement Platform (ARAMP) is a drifting ice or water borne platform to collect data from a variety of sensors, transmit selected results by Argos satellite, and store large data sets for later recovery or off-loading via RF telemetry. A typical sensor suite includes vector wind, barometric pressure, air temperature, humidity, compass, surface temperature, ice motion, broadband ambient noise, and upper ocean currents, temperature and conductivity. Optional sensors might include ice thickness, ablation, thermal conductivity and sonar radiation.

ARAMP is a four meter augmented spar buoy. A tower above supports an anemometer, meteorological sensors and antennas. A variable length cable below the spar provides power and communications to underwater sensors. A three-axis accelerometer for ice motion measurements is inside the buoy. Data collection is controlled by a powerful microcomputer that performs intelligent data sampling, spectral analysis of ambient noise, telemetry, data compression, and internal storage.

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## JASON JUNIOR: SYSTEMS DESIGN AND DEEP SUBMERGENCE VEHICLE INTERFACE

Christopher J. von Alt, Andrew D. Bowen and Emile M. Bergeron

The Remotely Operated Vehicle JASON Junior was designed to operate from a Deep Submergence Vehicle. The system is rated in accordance with U.S. Navy standards for equipment carried on a manned submersible which operates in up to 4,000 meters (13,000 feet) of water. All of the pressure housings have therefore been tested to 620 bar (9,000 p.s.i.).

An ROV such as JJ enhances the operational capability of a manned submersible in the following ways: it increases the submersible's standoff distance when it is operating in areas where it may become fouled; it permits detailed visual inspection, documentation and sampling in areas which are either inaccessible or which re-

quire penetration by the submersible; it increases the effective search area where quality photographic coverage may be obtained, as well as offering a different perspective of objects being surveyed; and most importantly, it provides a means of safe operation in otherwide hazardous situations.

This paper provides an overview of the design of the JJ system and its interface with ALVIN, a manned Deep Submergence Vehicle owned by the United States Navy and operated by the Woods Hole Oceanographic Institution.

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## INTEGRATION OF MULTI-DISCIPLINE DATA PROCESSING FOR EARTH OBSERVING SYSTEMS

Ralph Kahn and Robert P. Chase

Philisophically, there are two approaches to establishing a data and information system; it can be designed and built ab initio from a complete systems engineering analysis, or it can be assembled from existing hardware and software within the purview of a given organization. In the era of Earth System Science, characterized by research on increasingly multidisciplinary problems, a disparate collection of discipline-specific data systems must be made interoperable to the extent that a researcher hosted on one facility can easily access data, information, and a suite of services provided by and/or resident at other facilities. To meet this goal, it is unlikely that either of the two traditional approaches to developing data systems will be adequate by themselves, particularly given the complexity of the problem, the available time, the limited potential for large new increments in funding, and the substantial investment of resources and experience represented by existing facilities. Consequently, the NASA Earth Science and Applications community has been working toward greater interoperability of its data handling facilities from both perspectives simultaneously. In this paper we describe the first steps taken to provide for the controlled evolution of existing facilities toward greater interoperability and sharing of resources among the NASA-supported Earth Science and Applications data systems.

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## RECOVERY OF LOW-LEVEL RADIOACTIVE WASTE PACKAGES FROM DEEP OCEAN DISPOSAL SITES

Barrie Walden

The U.S. Atomic Energy Commission (AEC) licensed the ocean disposal of low-level radioactive waste (LLW) beginning in 1946. From that time until 1962, when land disposal was approved, waste was routinely embedded in concrete contained in steel drums and dumped primarily at three designated Atlantic and Pacific disposal sites with depths ranging between 900 and 3800 meters. Approximately 75,000 low-level radioactive waste packages were disposed of in this manner before ocean dumping was terminated in 1970 following the recommendations of the Federal Council on Environmental Quality in a report to the President.

Increased environmental concern for ocean waste disposal is evident in research, legislation, international treaties, and the activities of the U.S. Environmental Protection Agency (EPA), administrator of U.S. policy regarding ocean waste disposal. As a first step in developing effective controls, the EPA initiated a program designed to determine the effectiveness of past disposal techniques. Surveys of Atlantic and Pacific sites were conducted by the EPA in 1974 and 1975 using both manned and unmanned submersibles with the goal of assessing the physical condition of the containers and the near-field distribution of any released wastes.

Early controls on the packaging of the low-level radioactive waste were aimed at ensuring that the packages reached the bottom relatively intact; but standardization of size, shape, and internal configuration was not a requirement. As a result, the disposal packages were found to vary in size and weight with the majority being between 55 and 80 gallons, having weight in water of 550 to 1400 pounds (250 to 650 Kg); AEC regulations required a minimum of 550 pounds. Internal configurations frequently included an inner container housing the waste material surrounded by concrete, which filled the remainder of the drum. These containers were, in fact, pressure vessels with concrete walls and end caps, and many configured in this manner reached the bottom distorted as a result of implosion due to hydrostatic pressure.

The early EPA surveys pointed to the need for further information, particularly

in determining more precisely the contents and packaging techniques used in past disposal operations. In 1976, the Woods Hole Oceanographic Institution was awarded a contract to develop a method for recovering selected waste packages from the Atlantic disposal site to allow more detailed study. Operations conducted in July of that year resulted in the first attempted and successful recovery of an 80 gallon LLW package from a depth of 2800 meters. Subsequently, the method was used in 1977 to retrieve a LLW package from a depth of 900 meters at a Pacific site near the Farallon Islands, and again in 1978 in the Atlantic from a depth of 3800 meters. These were the first three radioactive waste packages retrieved from formerly used low-level waste disposal sites in the ocean.

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## A COMPARISON BETWEEN THE BORN AND RYTOV APPROXIMATIONS FOR THE INVERSE BACKSCATTERING PROBLEM

Subramaniam D. Rajan and George V. Frisk

A comparison is made between the Born and Rytov approximations in solving the inverse acoustic backscattering problem. A one dimensional problem is studied and it is shown that the Rytov approximation is better than the Born approximation in predicting sound speed changes whilst both methods have the same error in determining the positions of reflectors. This is shown analytically for simple models and numerically for more general models. It is also seen that the Rytov method is less sensitive to the reference sound speed employed in the inversion.

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## VAX SYSTEMS COEXISTING IN A MULTIVENDOR ENVIRONMENT

Robert C. Groman

VAX systems are very popular; however, there are many other computing options available including scientific workstations, super minicomputers and parallel processing systems. Networked personal computers are also available to the computer center and department level projects. This paper reviews the issues in designing, implementing and supporting a multivendor, networked environment.

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## THE HIGH PERFORMANCE OCEANOGRAPHIC MOORING (HIPOM)

Peter R. Clay and Henri O. Berteaux

In 1985 and 1986 the Ocean Structures and Moorings (OS&M) Laboratory of the Woods Hole Oceanographic Institution (WHOI) designed, deployed and recovered a High Performance Oceanographic Mooring in the Gulf Stream. This paper describes the need for this new type of mooring; the design features for substantially increasing the reliability and the performance of subsurface moorings set in strong current regimes; and the special instrumentation developed to monitor the mooring response. The paper then reviews the data acquired during the two month deployment and compares the HIPOM performance against the performance of previous moorings. Finally, recommendations for the design of future high current subsurface moorings conclude the paper.

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## THE DEEP SEA MOORINGS FISHBITE PROBLEM

Henri O. Berteaux, Dr. Bryce Prindle, Lt. Daniel May, NDBC

Evidence gathered to date clearly shows that moorings set far away from continental shores are subjected to severe fishbites. These bites occur from the surface to depths well within the bathypelagic zone, 1000 meters or more. The dimension of the fishbite problem is first reviewed. A data base which spans over twenty years and encompasses hundreds of moorings deployed world wide is used to delineate the space and time dependence of fishbite

attacks. This information is important when evaluating risks. Who are the culprits and why they do it is reviewed next. This knowledge is important when devising preventative methods. Granted that fish-bite damage is a real possibility, how does one distinguish it from other plausible causes of rope failure? Observations, laboratory procedures, and rationales used to answer this question with a fair degree of assurance are described next. Finally the paper reviews the preventive and the curative methods which hopefully can protect mooring lines from the mechanical damage inflicted by fish teeth.

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## GENERATION OF ACCRETING PLATE FABRIC AT FAST SPREADING AXES

ARGO RISE GROUP (Robert D. Ballard, J.L. Cheminee, J. Francheteau, R. Hekinian, W.C. Schwab, H. Sigurddson, Elazar Uchupi)

The ANGUS and ARGO systems were used to map the Neovolcanic Zone of a segment of the East Pacific Rise from just north of the Clipperton Fracture Zone at 10 degrees 15'N to 11 degrees 45'N including the overlap basin from 11 degrees 39'N to 11 degrees 46'N. The neovolcanic zone on the ridge east of the overlap basin is dominated by two generations of relatively recent sheet flow units (lava lakes) and associated collapse structures superimposed on an old sedimented pillow terrain. Recent volcanic activity along the western ridge is found only at the two axial highs at 10 degrees 55'N and 11 degrees 26'N and the intervening low at 11 degrees 15'N. Activity on this western ridge is restricted to a narrow axial graben and horst. The floor of the overlap basin consists mainly of old sedimented pillows. On the eastern ridge hydrothermal vents occur within the collapse structures, and on the western one along the crests of the fault complexes flanking the axial horst and graben. These observations tend to support the concept that magmatic activity along spreading axes is episodic and that such activity is not continuous throughout the ridge.

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WHOI Contribution No. 6497.

## CODED PULSE-COHERENT DOPPLER SONAR

Blair H. Brumley and Eugene A.Terray

We describe the use of coded pulse trains to improve the range velocity ambiguity of pulse-coherent Doppler sonar. Laboratory results will be presented, together with a discussion of the performance of a Doppler estimator based on Fourier transform methods. An instrument incorporating these ideas and intended for high-resolution turbulence measurements is briefly described.

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## UNDERWATER IMAGERY USING AN ELECTRONIC STILL CAMERA

Stewart E. Harris, Robert H. Squires, and Emile M. Bergeron

Underwater images are generally characterized by low contrast caused by backscatter, the subject matter itself and poor illumination, especially large area images. Traditional sensors, such as SIT TV cameras and film have been used together in systems to complement each other, but film is not well matched in sensitivity to the SIT camera.

An underwater electronic still camera has been developed which represents a major advance in our ability to achieve high quality, underwater visual images with large area coverage. Using high performance, large format CCD imagers, the electronic still camera takes photographic quality images at longer ranges with real-time image display and processing capability.

This paper will discuss the at-sea test of our prototype camera. The CCD device used has a frame transfer architecture designed to maximize sensitivity and reduce noise yielding an incredible dynamic range of 76 dB. This characteristic enables us to resolve small changes in contrast inherent in underwater images. Presented here is a description of the camera and its potential application.

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WHOI Contribution No. 6514.

## UPPER OCEAN DYNAMICS

James F. Price, Eugene A. Terray and Robert A. Weller

Research on upper ocean dynamics has contributed steady progress towards a more complete and useful understanding of the ocean's role in air/sea interaction and climate. High resolution models of the upper ocean thermal structure are now quite realistic, and in some applications are limited as much by uncertainties in the surface heat flux as by uncertainties in model physics. Low resolution upper ocean thermal models are routinely included in most climate models, and have been shown to give far better simulations than do simple slab or heat conduction models. Some of these climate models have provided important new insights into the mechanisms by which the ocean may respond to a future greenhouse-imposed surface heating anomaly.

In contrast, the structure of the upper ocean wind-driven velocity is not so well understood. Some models and high quality field data show significant sustained vertical shears within the temperature mixed-layer, while other data sets show organized, energetic, three-dimensional flow structures. Still other field data appear to reveal a velocity mixed-layer very much like the thermal mixed-layer. Thus the structure of the upper ocean velocity is an important and still open issue for dynamics and models, and also for the interpretation of the large and rapidly growing drifting buoy data base.

The role of surface waves in generating and maintaining this current structure also remains poorly understood. Waves certainly play a central role in the mechanics of momentum transfer across the air-sea interface, both through surface roughness and more directly as a consequence of breaking. The combined system of waves and wind-driven currents is also known to be unstable, and their interaction may be an important mechanism for producing certain types of organized convection in the mixed-layer.

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WHOI Contribution No. 6530.

## DEVELOPMENT OF A PRACTICAL COHERENT ACOUSTIC DOPPLER CURRENT PROFILER

Ramon Cabrera, Kent Deines, Blair Brumley and Eugene Terray

The practical feasibility of developing a Coherent Acoustic Doppler Current Profiler (ADCP) with spatial resolution and range comparable to those of commercially available incoherent systems but with much smaller velocity measurement variance is being studied. This improvement in measurement accuracy will reduce required averaging times, thus permitting the observation of short time-scale currents (i.e. internal wave breaking) which are beyond the capabilities of available incoherent ADCP's. Several strategies have been analysed and tested. Among them, transmission of coded acoustic pulses combined with coherent signal processing techniques has been given special attention. This approach may allow the measurement of watermass velocities with high accuracy without the range limitations of conventional pulse-to-pulse coherent systems due to velocity ambiguity and pulse-to-pulse decorrelation. Several schemes based on this approach have been analysed and their relative merits assessed.

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## THE INTERPRETATION AND EVALUATION OF A 3 MHz ACOUSTIC BACKSCATTER DEVICE FOR MEASURING BENTHIC BOUNDARY LAYER SEDIMENT DYNAMICS.

Charles Libicki, Keith W. Bedford and James F. Lynch

For ultrasonic backscatter devices to be of aid in studies of turbulent sediment transport dynamics, the procedures for converting signal to concentration estimates should be as accurate as possible, and the space and tie resolution should be as high as possible. Signal conversion for the three MHz system considered here takes into account near-field beam pattern effects on

propagation, and attenuation. Enhancing resolution involves explicit consideration of various sources of noise and interference. The results of field deployments demonstrate that with signal conditioning and ensemble averaging, signal-to-noise ratios can be achieved that allow turbulent variation in concentrations to be measured. Two possible sources of error in the conversion procedure are: 1) in situ measurements of attenuation due to scatterers is not measured, but must be estimated from the data, and 2) with a single-frequency beam, the effects on scattering response of concentration variation and particle-size variation can not be uncoupled.

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WHOI Contribution No. 6528.

## IMAGING THE NEOVOLCANIC ZONE OF THE EAST PACIFIC RISE, NORTH OF THE CLIPPERTON FRACTURE ZONE (10 degrees 15'N - 11 degrees 53'N)

ARGO RISE GROUP (R. Ballard, J.L. Cheminee, J. Francheteau, R. Hekinian, W.C. Schwab, H. Sigurddson, Elazar Uchupi)

Still photographs and video images recorded along the neovolcanic zone of the East Pacific Rise from 10 degrees 15'N to 11 degrees 53'N show that recent volcanic activity (sheet flows less than 100 years old) is superimposed on an older sediment-laden pillow terrain greater than 7000 years old. On the eastern ridge-segment of overlapping spreading centres located between 11 degrees 40'N and 11 degrees 55'N, the recent activity occurs in two closely spaced regions whereas on the ridge segment west and south of the overlapping spreading centres, recent volcanic activity was noted on two topographic highs at 10 degrees 55'N and 11 degrees 26'N, where it is mostly confined to an axial graben. Spatial and temporal relationships between the pillow flows and the younger volcanic units indicated that magmatic activity is episodic and discontinuous along the neovolcanic zone. We propose that the magmatism follows a cyclical pattern, progressing from initial pillow lava emplacement to extrusion of sheet flows to a waning phase of pillow extrusion and finally to pelagic sedimentation.

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WHOI Contribution No. 6546.

## TRAJECTORY CONTROL OF NON-LINEAR, TIME-VARYING DISCRETE-TIME SYSTEMS USING DISCRETE-TIME SLIDING CONTROL

David M. DeLonga, Jean-Jacques E. Slotine and Dana R. Yoerger

An effective low-level control system is a key component in the successful implementation of any high-level supervisory control scheme. The Deep Submergence Laboratory at the Woods Hole Oceanographic Institution is currently developing supervisory control system methodologies for underwater vehicles and manipulators as part of the ARGO/JASON program. The design of this low-level controller is particularly challenging because of the fluidic environment in which such underwater systems operate. These environmental effects, when compounded by the uncertain, nonlinear dynamics that characterize such systems, require the use of control techniques beyond traditional methods to ensure reliable and predictable performance.

A new discrete-time control methodology, based on continuous-time sliding control concepts, is presented in this paper in order to explicitly account for the digital implementation of the controller. The methodology directly addresses the control of systems with nonlinear, time-varying dynamics with uncertain parameters. Quantifiable modeling-performance tradeoffs are obtained while accounting for the presence of high-frequency unmodeled system dynamics. The discrete-time sliding control method is demonstrated in simulation and compared to a continuous-time sliding controller.

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WHOI Contribution No. 6627.

## THE ADVANCE OF A SALT WEDGE FRONT: OBSERVATIONS AND DYNAMICAL MODEL

Wayne R. Geyer

The salinity intrusion in the Fraser River estuary, British Columbia, is subject

to large variations due to strong tidal flow. The salt wedge front propagates as much as 18 km during the flooding tide, and it is flushed entirely out of the estuary in the highly sheared ebb flow. Detailed measurements of velocity and water properties provide the basis for theoretical and numerical modelling of the interaction between the barotropic and density-driven flows. The bottom boundary layer has a pronounced influence on the speed and structure of the density-driven flow. Of particular note is a sharp velocity-maximum near the center of the pycnocline, in which the local velocity exceeds the speed of the intrusion by as much as 0.4 m/s. Theoretical analysis of the velocity structure indicates that turbulence is sharply attenuated in the vicinity of the velocity-maximum, consistent with a Richardson number cut-off of the stratified turbulence. A two-layer model is applied to the motion of the salinity front with a moving boundary condition at the head to the salt wedge. The model-predicted propagation speed and spatial structure compare favorably with observations, indicating that the two-layer representation contains the essential elements of the dynamics of this highly stratified flow.

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WHOI Contribution No. 6536.

## A NON-DETERMINISTIC APPROACH TO 3-D MODELING UNDERWATER

W. Kenneth Stewart

A framework for multisensor exploration of underwater environments is presented with results of applications in 3-dimensional sonar mapping. A multidimensional model provides the basis for extracting information relevant to concurrent real-time processes. Probabilistic methods account for non-ideal sensors while spatial decomposition and numerical techniques treat amorphous underwater features and allow an incremental approach to representing the surroundings. No all-encompassing theory is advocated. A plausible kit of multidisciplinary tools has shown immediate benefits when applied to subsea tasks. Computer simulations and field applications with profiling and imaging sonars aboard ships, towed platforms, and remotely operated vehicles offer supporting evidence in the areas of underwater archaeology, geological mapping, and search operations.

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WHOI Contribution No. 6556.

## A NEW METHOD FOR EVALUATING THE LOG-LIKELIHOOD GRADIENT (SCORE) OF LINEAR DYNAMIC SYSTEMS

Mordechai Segal and Ehud Weinstein

A new method for evaluating the log-likelihood gradient, or the score, of linear dynamic systems is presented, based on the optimal smoothing equations. The new result can be used for efficient calculations and approximations of gradient-search algorithms for maximum likelihood estimation of the unknown system parameters.

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WHOI Contribution No. 6559.

## MAXIMUM LIKELIHOOD PARAMETER IDENTIFICATION OF CONTINUOUS-TIME LINEAR DYNAMIC SYSTEMS GIVEN DISCRETE-TIME OBSERVATIONS

Mordechai Segal and Ehud Weinstein

The problem of parameter estimation of continuous-time linear dynamic systems via discrete-time observations is considered. A new approach is presented, based on the Estimate-Maximum (EM) algorithm, that exploits the continuous state equation hidden underneath the discrete-time observations. The proposed algorithm converges, under certain regularity conditions, to a stationary point of the likelihood function where each iteration cycle increases the likelihood of the estimated parameters. We also present a new method for evaluating the log-likelihood gradient (score), the Hessian, and the Fisher's information matrix (FIM) using the optimal smoothing equations, which can be used in conjunction with gradient-search methods to accelerate

the proposed algorithm, and for assessing the mean square estimation accuracy.

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WHOI Contribution No. 6564.

## ONE TURN OF THE SCREW: A SIMPLE TECHNIQUE FOR FINE-SCALE, VERTICAL SECTIONING OF FRESH SEDIMENT CORES

Charlotte M. Fuller and Cheryl Ann Butman

A simple technique is described for vertical sectioning of fresh sediment cores at scales of millimeters. This core extruder operates on the same general principle as previously described piston-type extruders (small syringes) for fine-scale sectioning, but can be used on larger core tubing. Calibration experiments to define the precision of the technique for sectioning at 2-mm increments indicate that deviations of extruded grain size distributions from those initially layered in the cores are within the measurement and technician error for the experiments. Virtually no smearing was observed visually, using white clay layers, or empirically, from extruded grain-size distributions. Vertical positioning is precise to within ç 1 % of a 2-mm horizon thickness. The resolution of sediment stratigraphy is primarily limited by the maximum grain size at the interface between adjacent sediment layers. Because stratigraphic resolution is also limited by disturbances to the sediment column during initial sampling, this extruder was originally designed for use with diver-collected cores. For sampling in deep water, we also describe a technique for subsampling a box core with cylindrical core tubes while the box core is biting. This eliminates the potential error introduced when subsampling the sediments after the box core is brought on deck. Results from using the extruder on field cores collected in a shallow, subtidal muddy habitat indicate the importance of fine-scale vertical sectioning in studies of sediment transport phenomena, because grain-size distributions in the very near surface ("resuspendable") fraction of the sediment column may be substantially different from distributions integrated over an inappropriately larger (e.g., 2 cm) interval.

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WHOI Contribution No. 6192.

## THE IMPORTANCE OF BOUNDARY-LAYER FLOW PROCESSES IN SUPPLYING PHYTOPLANKTON TO THE BENTHIC SUSPENSION FEEDER *Mytilus edulis* L.

Marcel Frechette, Cheryl Ann Butman and Wayne R. Geyer

The importance of boundary-layer flow processes in controlling the supply of food to benthic suspension feeders was investigated through field observations and numerical modelling. Time-series field measurements of phytoplankton fluorescence and current speed above an intertidal mussel bed and of in-situ mussel bed consumption indicated that fluorescence and flow decreased toward the bed and that both near-bed fluorescence and consumption were positively correlated with current speed. The reduced fluorescence in the bottom-most water samples may be attributed to consumption by mussels; a quasi-steady suspended-food concentration could be maintained by turbulent flux from the overlying water, where phytoplankton is relatively abundant. As velocity increases, the turbulent flux increases, causing an increased supply of food to the mussel bed and a corresponding increase in consumption. A near-bed steady-state concentration of phytoplankton would be maintained by advection. The field measurements provide observations only of vertical variations, so a numerical model was used to ascertain the combined influence of advection and vertical turbulent diffusion on phytoplankton concentration over a mussel bed and on mussel-bed consumption and growth.

Model results are consistent with presently available field data on phytoplankton distributions and mussel growth. The vertical distribution of phytoplankton is determined by the structure of the boundary-layer flow. Bed roughness attributable to mussels sufficiently increases the boundary shear stress to increase the vertical mixing in the flow, enhancing the supply of phytoplankton to the mussels. This results in enhanced growth and productivity of the mussel bed, since field data suggest

that mussel feeding rates are supply-dependent. Under certain flow and phytoplankton conditions, the extent of mussel beds in the direction of the mean current may be limited by phytoplankton supply--when upstream organisms deplete near-bed waters of phytoplankton faster than they can be replenished by vertical mixing and advection. This also explains the frequent observation that larger mussels occur at the leading edges of mussel beds and suggest that there may be an optimal mussel-bed size to maximize individual growth. In addition to bed roughness, model predictions of phytoplankton concentration were highly dependent on the mussel intake height above the bed. Thus, larger mussels and mussels growing on the crest of hummocks are expected to experience the best feeding conditions.

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WHOI Contribution No. 6581.

## SUBSTRATE CHOICES MADE BY MARINE LARVAE SETTLING IN STILL WATER AND IN A FLUME FLOW

Cheryl Ann Butman, Judith P. Grassle and Christine M. Webb

Laboratory studies of substrate selection by settling planktonic larvae of the infaunal polychaete, Capitella sp. I, and the infaunal bivalve, Mercenaria mercenaria, were conducted in still water and in a steady, unidirectional, turbulent, flume flow. In separate experiments, each species was given the choice of a natural muddy sediment or a glass bead mixture in a five-by-five compartment sediment array, where the treatments were alternated in a checkerboard design. In still water, both species clearly chose one treatment over the other: the worm larvae preferred the natural mud, while the clam larvae preferred the glass beads. These results are consistent with the food requirements of the adults. In the flume flow, settled worms were again more abundant in the natural mud, but the clams were evenly distributed between the two sediment treatments. Differences in behaviors of the competent larvae may partially explain these results.

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WHOI Contribution No. 6603.

## AN ARCTIC REMOTE AUTONOMOUS MEASUREMENT PLATFORM

Kenneth E. Prada and Arthur B. Baggeroer

The perpetual ice cover in the Arctic has inhibited broad analysis of the properties of the Arctic Ocean. Ice camps established at various sites have collected valuable data at or near the camp site. Research ships have ventured into a small number of areas to perform short term programs. However, the temporal and spatial coverage of all scientific disciplines is insufficient to provide a detailed analysis of the important properties of the Arctic Ocean. Satellite borne sensors have expanded the coverage, but only within the resolution, accuracy and depth provided by these sensors. A clear need has developed for a multidisciplinary data collection tool to provide expanded coverage in ice covered regions.

The Arctic Remote Autonomous Measurement Platform (ARAMP) is a tool to provide for these needs. ARAMP is a free drifting ice implanted platform (buoy) that will collect data from a variety of sensors, transmit selected results by Argos satellite, and internally store other large volume data sets for later physical recovery or off-loading via high speed RF telemetry. Its design objective is to provide measurements of a wide range of physical parameters both above and below the ice. A typical suite of sensors includes:

-vector wind -sea surface temperature
-barometric pressure -ice motion and dynamics
-air temperature -broadband ambient noise
-humidity -upper ocean currents, temperature
-compass and conductivity

Optional sensors might include:

-ice thickness -ice thermal conductivity profile
-ice ablation -solar radiation

ARAMP consists of a four meter augmented spar buoy, tapered for easy insertion and removal in a ten inch ice hole. A three meter tripod tower mounted atop the spar provides support for an anemometer, meterological sensors and telemetry antennas. A cable of variable length is suspended below the spar and provides mechanical and electrical support for temperature, pressure, conductivity, current and hydrophone sensors. The spar housing contains a sensitive three-axis accelerometer for high resolution measurements of ice motion.

The data collection system is controlled by a powerful microcomputer that performs intelligent data sampling, real-time spectral analysis of ambient noise data, data telemetry, and data compression and internal storage. ARAMP uses a standard communications protocol and can address any number of sensors on the suspended cable, within the buoy, or on the ice outside the buoy.

Submitted to: IEEE/MTS Workshop on Polar Measurements and Instrumentation.

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WHOI Contribution No. 6608.

## SAMPLING AND INVERSION OF DATA IN DIFFRACTION PARTICLE SIZING

James B. Riley and Yogesh C. Agrawal

In optical diffraction particle sizing, a numerical transform is sought so that a particle size distribution can be determined from angular measurements of near forward scattering. In this paper, we consider the nonuniqueness and instability of this transform, for discrete data. Our arguments are based on approximation of the kernel by a function to which it is asymptotic. The results, which include an angular sampling criterion, and a rescaling of the forward transform, are applied to choosing and developing algorithms for inverting experimental measurements of scattering. Measurements of scattering from distributions of polystyrene spheres are successfully inverted.

Submitted to: Applied Optics.

Supported by: NASA Traineeship grant (NGT-014-800 Supplement 5) and Coastal Research Laboratory of the Woods Hole Oceanographic Institute and ONR N00014-82-C-0019.

WHOI Contribution No. 6626.

## RELATIONS BETWEEN BELINI-TARTARA, CHAZAN-ZAKAI-ZIV, AND WAX-ZIV LOWER BOUNDS

Ehud Weinstein

A class of lower bounds on the mean square error in parameter estimation is presented, based on the Belini-Tartara lower bound. The Wax Ziv lower bound is shown to be a special case in the class. These bounds tend to be significantly tighter than the Chazan-Zakai-Ziv lower bound when the parameter to be estimated is subject to ambiguity and threshold effects.

In press: IEEE Transactions on Information Theory, November 1987.

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WHOI Contribution No. 6588.

## A FINITE DEPTH WIND-WAVE MODEL PART 1 - MODEL DESCRIPTION

Hans C. Graber and Ole S. Madsen

A parametric windsea model for arbitrary water depths is presented. The model is derived from a conservation of energy flux formation and includes shoaling, refraction, dissipation by bottom friction, as well as finite depth modifications of the atmospheric input and nonlinear wave-wave interaction source terms. The importance of dissipation due to a rough ocean floor on the migration of the spectral peak frequency is discussed and compared with the same effect by the nonlinear energy transfer. Numerical simulations are used to systematically examine wave growth and the development of the spectral peak in a depth limited ocean.

Two idealized situations of wave growth and propagation are considered to further understand the influence of bottom friction on the spectral dynamics. The first case studies the characteristics of fetch-limited wave growth in a steady, uniform wind as function of depth and bottom roughness. The second case examines the role of bottom dissipation on a fully developed deep water spectrum propagating up a constant slope under a steady onshore blowing wind. For case 1 the growth curves and peak frequency development are plotted as a function of fetch and wave spectra

for infinite fetch and duration are shown for all depths and wave friction factors. For case 2 the evolution of total energy and peak frequency along the shelf slope are drawn for stationary conditions as well as the stationary inshore energy spectra.

This numerical study reveals the following: (a) bottom friction is a finite depth mechanism as important as the nonlinear energy transfer in controlling the spectral shape in shallow water; (b) under the influence of bottom dissipation the positive energy transfer from wave-wave interactions to lower frequencies is reduced and causes the spectral peak to wander towards higher frequencies; (c) equilibrium energy spectra in finite depth depend on depth and bottom roughness and occur when the nonlinear energy transfer and bottom friction source terms approximately balance each other.

Submitted to: Journal of Physical Oceanography.

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WHOI Contribution No. 6595.

## DEVELOPMENT OF A PRACTICAL COHERENT ACOUSTIC DOPPLER CURRENT PROFILER

Ramon Cabrera, Kent Deines, Blair Brumley, and Eugene Terray

The practical feasibility of developing a Coherent Acoustic Doppler Current Profiler (ADCP) with spatial resolution and range comparable to those of commercially available incoherent systems but with much smaller velocity measurement variance is being studied. This improvement in measurement accuracy will reduce required averaging times, thus permitting the observation of short timescale currents (i.e. internal wave breaking) which are beyond the capabilities of available incoherent ADCP's. Several strategies have been analysed and tested. Among them, transmission of coded acoustic pulses combined with coherent signal processing techniques has been given special attention. This approach may allow the measurement of watermass velocities with high accuracy without the range limitations of conventional pulse-to-pulse decorrelation. Several schemes based on this approach have been analysed and their relative merits assessed.

Submitted to: Oceans '87, June 1,1987.

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WHOI Contribution No. 6531.

## A SYSTEMS-APPROACH TO THE DESIGN OF THE EOS DATA AND INFORMATION SYSTEM

Robert R.P. Chase

The task of designing a data and information system responsive to the needs of Eos users is stratified by level and approached with contemporary systems design practices. Appropriate systems design principles are applied at the conceptual design level in this paper. A functional, architectural design is described in terms of elemental composition, top-level functions, and external and internal interfaces. The functional validity of this design has been tested and verified through the use of realistic user scenarios consistent with existing plans for the 1990's, the Space Station era. Technologic and management impediments to the development of the requisite data and information system for Eos are examined and a consistent methodology for developing this system is discussed.

Submitted to: IEEE IGARSS Digest.

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WHOI Contribution No. 6443.

## LASER VELOCIMETRY FOR BENTHIC SEDIMENT TRANSPORT

Yogesh C. Agrawal and Chris J. Belting

Two deep sea laser Doppler velocimeter (LDV) systems are described. The first, a backscatter instrument, measures the two horizontal components of velocity at a programmable sequence of heights above the seafloor, from a few cm's to roughly 40 cm. The second instrument, a forward scatter system, measures the downstream and verticle velocities in an inverted bottom flume, SeaDuct, thereby also obtaining the Reynold's stress. Both instruments sample the velocity at 32 Hz although the actual velocity 'realization' rate for the backscatter instrument depends strongly on the suspended mass concentration in the water column. In this paper we describe the LDV instrumentation and present example data. The observations with the backscatter system in natural flows were taken at the HEBBLE site in water depth of 4815 m and over a region of microtopography. These suggest departure

of the velocity profile from the logarithmic wall layer which may be due to the lack of statistical stationarity, but a consistent change in direction of flow over the short range of heights suggests steering by bottom bedforms. The turbulent kinetic energy appears to vary weakly near bottom. Data from the SeaDuct system at a fixed height, taken at USGS site °Q', indicate constancy of the drag coefficient and the ratio of stress to total turbulent intensity. The stress-suspended load relationship for the sediment at this site shows large erosion at low stress, with no evidence of a critical stress for initiation of motion.

In Press: Deep Sea Research, July 1987.

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WHOI Contribution No. 6535.

## A MODEL DEPENDENT METHOD FOR INVERTING VERTICAL PROFILES OF SCATTERING TO OBTAIN PARTICLE SIZE SPECTRA IN BOUNDARY LAYERS

James F. Lynch and Yogesh C. Agrawal

A method is presented to obtain particle size spectra from verticle profiles of scattering strength in planetary boundary layers. It is assumed that the boundary layer is horizontally homogeneous, and that the vertical turbulent diffusion of particles can be modelled from a knowledge of the surface friction velocity. Equilibrium boundary layer profiles for each class of suspended particles are assumed to be established resulting from the balance between vertical turbulent diffusion and gravitational settling. The forward problem thus models the depth-dependent scattering as the sum across size classes weighted by number density and scattering cross section in accordance with established scattering theory. Constrained inverses produce the size spectra. Results of inversions from synthetic ocean data are presented for optical transmissometry and acoustic backscattering. Inversions of acoustic field data from the HEBBLE experiment are also presented. Finally, the applications of the work presented for the design of ocean boundary layer experiments, its application in other fields, and the directions for future research are discussed.

Submitted to: Deep Sea Research.

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WHOI Contribution No. 6653.

## VELOCITIES AND REYNOLDS STRESS UNDER WAVES USING LASER VELOCIMETRY

Yogesh C. Agrawal, F. Dias and David G. Aubrey

Observations of the velocity field and Reynolds stress on the seafloor under waves reported from a field experiment over rippled topography. The velocity field was observed at 32 Hz sample rate with a sample volume size of 200 micron diameter and 3 mm length, using a submersible two axis laser Doppler velocimeter. The velocimeter was mounted on a special platform which permitted orienting the instrument sequentially at $\pm$ 45 degrees to the nominal oncoming wave direction, and at a number of depths. The data set also included the observation of the pressure, sampled at 2 Hz. The velocity was separated into two parts: a wave-coherent part and a residual turbulent part. The stress was estimated from the turbulent parts of the horizontal and vertical velocity obtained in this manner. One second averaged stress series indicated stresses with small means, of order 0.1 dynes.cm with large variance. No periodic behavior of the stress or the turbulent intensity was discernible at the peak wave frequency. Our friction factor estimate of 0.25 is consistent with estimates of earlier investigators. This is despite disagreement between our field observation of a lack of periodicity in the stress, and the observation of a wave-forced periodicity in earlier laboratory work. The velocity spectra indicate a -5/3rd slope region over two decades of frequency.

Submitted to: Journal of Physical Oceanography.

Supported by: ONR N00014-87-C-001.

WHOI Contribution No. 6658.

## AN EXPERIMENTAL INVESTIGATION OF THE QUASI-STATICS AND DYNAMICS OF A LONG VERTICLE TOW CABLE

Dana R. Yoerger, Mark A. Grosenbaugh, Michael S. Triantafyllou, Knut Engebretsen, and James Burgess

This report presents preliminary results of a unique experiment examining the static and dynamic characteristics of long vertical tow cables. The experiment was

conducted at the U.S. Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) and combined acoustic tracking of cable position with simultaneous measurements of cable acceleraton. The cable used was the 1.73 centimeter diameter steel-armored coaxial cable that has emerged as a standard in the oceanographic community. Cable lengths between 800 m and 1200 m at tow speeds up to 1 m/s were studied. Quasi-static configurations were measured by monitoring the position of acoustic pingers attached to the cable. A drag coefficient was estimated by comparing the measured cable shape to computed shapes. A value of 1.6 gives the best fit to the experimental data. Five self-recording instrument packages were attached to the cable to observe high frequency cable motion. Spectral analysis shows large amounts of energy near the Strouhal frequency and its higher harmonics.

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WHOI Contribution No. 6662.

## LARGE APERTURE TIME-SERIES OCEANIC SEDIMENTTRAPS: DESIGN OBJECTIVES, CONSTRUCTION AND APPLICATION

Susumu Honjo and Kenneth Doherty

We developed sediment traps with 0.5 and 1.15 m apperatures which are capable of collecting 12 to 25 samples at programmed intervals, typically weekly or bimonthly, during one continuous semi- to interannual deployment. We applied a number of new synthetic materials and stable metallic components to ensure reliable, long-lasting performance at oceanic depth. The key component of the trap is a set of sequentially rotating samplers which is driven by a microprocessor-controlled electronic stepping motor. The electronic power controller controls sampler exchange with a high degree of flexibility and precision, as well as independently recording the executed sampling events. Each sampling bottle is sealed from ambient water during the time samples are storaged before recovery. After continuous improvement and modification during 29.5 deployment-years since 1982, we are convinced that these sediment traps can provide a relatively large quantity of oceanic particle fluxes in time series with high experimental reliability.

Submitted to: Deep Sea Research.

Supported by: NSF OCE8208736, OCE8517106 (Chemical Oceanography) Hand contracts from the Office of Naval Research.

WHOI Contribution No. 6389.

## A MODEL-BASED APPROACH TO 3-D IMAGING AND MAPPING UNDERWATER

W. Kenneth Stewart

An approach to multidimensional representation of underwater environments is presented with results of applications in 3-dimensional sonar mapping. A non-deterministic model incorporates information from multiple knowledge sources and creates a framework for real-time processing. Probabilistic methods account for non-ideal sensors while spatial decomposition and numerical techniques treat amorphous underwater features and allow an incremental approach to modeling the surroundings. An emphasis on representational and modeling issues is maintained with examples drawn from computer simulations and field data from profiling and imaging sonars.

Submitted to: ASME, Proc. Conf. on Offshore Mech. and Arctic Eng.

Supported by: MIT Sea Grant.

WHOI Contribution No. 6596.

## FIBER OPTIC TOW CABLE

Christopher von Alt

Historically, the design of deep ocean tethered vehicle systems has been a highly constrained process. The dominant constraints involve the long cable which runs from the surface to the vehicle. They are: a lack of transferred power, a lack of available noise immune bandwidth, and the fact that a comfortable safety factor can not be obtained for envisioned payloads.

The Deep Submergence Laborabory (DSL) of the Woods Hole Oceanographic Institution (WHOI) has been funded to develop and test a prototype deep ocean cable which will address these issues. The proposed solution, an electro-optical mechanical cable which outwardly conforms to the current University National Oceanographic Laboratory System (UNOLS) standard coaxial cable, is presented along with a discussion of the constraints placed on its design and its proposed methods of use in the ARGO-JASON system presently under development at DSL.

Additionally, results of investigation into the capabilities, cost size, and robustness of commercially available electro-optical telemetry systems are included. Along with this, proposed methods of cable termination and splicing are presented.

Submitted to: Oceans '87.

Supported by: National Geographic Society Grant No. 3300-86.

WHOI Contribution No. 6454.

## A NEW CLASS OF SEQUENTIAL ALGORITHM FOR PARAMETER ESTIMATION

Ehud Weinstein, Meir Feder, Alan V. Oppenheim

We use the method of stochastic approximation to convert iterative algorithms for maximizing the Kullback-Lieber information measure into sequential algorithms. Special attention is given to the case of imcomplete data, and a variety of algorithms are presented to deal with situations of that kind.

Submitted to: Proceedings of the IEEE.

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WHOI Contribution No. 6578.

## PARAMETER ESTIMATION OF SUPERIMPOSED SIGNALS USING THE EM ALGORITHM

Meir Feder and Ehud Weinstein

We develop a computationally efficient algorithm for parameter estimation of superimposed signals based on the EM algorithm. The idea is to decompose the observed data into its signal components, and then to estimate the parameters of each signal component separately. The algorithm iterates back and forth, using the current parameter estimates to better decompose the observed data, and thus to increase the likelihood of the next parameter estimates. The application of the algorithm to the multipath time-delay and to the multiple source location estimation problems is considered.

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Supported by: ONR N00014-85-K-0272.

WHOI Contibution No. 6584.

## A GENERAL CLASS OF LOWER BOUNDS IN PARAMETER ESTIMATION

Ehud Weinstein and Anthony J. Weiss

We formulate a general class of Bayesian lower bounds on moments of the error in parameter estimation and show that the Cramer-Rao, the Bhattacharyya, the Bobrovsky-Zakai, and the Weiss-Weinstein lower bounds are special cases in the class. The bounds can be applied to the estimation of vector parameters and any given function of the parameters.

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WHOI Contribution No. 6587.

## THE GEOLOGY OF THE TITANIC SITE AND VICINITY

Elazar Uchupi, Maureen T. Muck, and Robert D. Ballard

The southern approaches to the RMS Titanic site are dominated by Cameron Canyon whose floor is carpeted by sediment debris and slumps, and an area of bottom current bedforms that we have designated the Titanic Sediment Wave Field. This field, characterized by barchan dunes, sand ribbons and sheets, and mud waves owes its origin to the Western Boundary Undercurrent. North of the field is the RMS Titanic site. The hull which is in two parts 600 m apart apparently broke in two at the surface with the stern section sinking directly to the bottom, and the bow following a more gradual descent to its final resting place.

Submitted to: Deep Sea Research.

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WHOI Contribution No. 6671.

# EFFECTS OF BOUNDARY-LAYER FLOW ON THE SETTLEMENT OF ORGANISMS ONTO FLAT PLATES: PRELIMINARY RESULTS FROM CROSS SEAMOUNT

L.S. Mullineaux, Cheryl A. Butman, Charlotte M. Fuller

Boundary-layer flow conditions may influence the supply of invertebrate larvae to benthic habitats, and their behavior during settlement. The response of larvae of deep-water, encrusting organisms to different flow conditions was investigated by deploying two thicknesses of settlement plates on the summit of Cross Seamount, Central North Pacific (410 m water depth). Currents were measured 1.8 m above the study site during the 48-day experiment. These measurements were combined with dissolution rates of alabaster disks and previous laboratory flume studies to describe the flow patterns expected over the settlement plates. Settlement of organisms (mostly benthic foraminifers) onto 1-cm-thick Lexan plates was significantly greater than onto 0.15-cm thick plates, possibly because of advantageous settlement environments in eddies formed at the edges of thick plates. Ferromanganese-coated plates were also deployed to see if larvae actively selected substrates similar to their natural habitat.

Submitted to: NOAA Symposium Report 6(2), 1988.

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WHOI Contribution No. 6694.

# DEPARTMENT OF PHYSICAL OCEANOGRAPHY

Robert C. Beardsley, Chairman

# COASTAL CIRCULATION AND DYNAMICS

## ON THE EFFECT OF BOTTOM FRICTION ON INTERNAL WAVES

K. H. Brink

The problem of internal waves with bottom friction is formulated in a general form, and solved for an example where damping is relatively weak. The decay time for damping is not strongly dependent on frequency or stratification, but the decay distance is. These results appear to help rationalize the observed tendency for internal tides over the continental shelf to be weaker during periods of weak stratification than during strong stratification.

In press: Continental Shelf Research

Supported by: ONR Contract N00014-84C-0134, NR 083-400.

WHOI Contribution No. 6518.

## SHELF AND SLOPE CIRCULATION INDUCED BY FLUCTUATING OFFSHORE FORCING

David C. Chapman and Kenneth H. Brink

A linear model which includes continuous vertical stratification, arbitrary cross-shelf bottom topography, and bottom friction is used to examine the response of shelf and slope waters to fluctuating offshore forcing in the form of a specified pressure field. For forcing which is periodic in the alongshore direction and in time, the response varies dramatically with frequency. For periods of less than about 10 days, the response is dominated by near resonancies with free coastally trapped waves. These are not pure resonances because of the mismatch between the forcing structure and the free wave structure. For periods of greater than about 10 days, the velocity response decays away from the forcing with a scale determined by the projection of the forcing onto the flat-bottom baroclinic modes, typically the first baroclinic Rossby radius. If the continental slope is encountered within this scale distance, then the flow is altered and creates a bottom-trapped, alongshore velocity maximum seaward of the shelf break. Increased stratification enhances bottom trapping and inhibits flow across the slope, moving the maximum in alongshore velocity seaward, thus reducing the alongshore flow near the shelf break. The shelf response is always weak and barotropic. Furthermore, the slope response is largely independent of the shelf geometry, suggesting that narrow shelves appear to be more easily influenced by offshore forcing only because their coasts are closer to the forcing. The model is used to simulate the response to a Gaussian-shaped anticyclonic eddy translating uniformly in the alongshore direction. The eddy flow is blocked by the topography and becomes squashed at the shelf break. Some shelf water is entrainedcreating a weak shelf circulation cell. The shoreward flow in the eddy cannot move onto the shelf and instead forms an along-shore jet near the shelf break. The jet extends away from the eddy in the direction toward which free coastally trapped waves propagate, but the alongshore velocity within the jet is opposite to the alongshore velocity within the eddy.

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WHOI Contribution No. 6516.

## OCEAN CURRENTS OVER THE CONTINENTAL SLOPE

G. T. Csanady

In recent years much has been learned about currents over the relatively steep bottom of continental slopes. Flow crossing depth contours of sloping bottom is strongly influenced by vortex stretching. In cases where the flow is geostrophic vortex stretching is equivalent to bottom pressure torque. Depending on what physical effect counteracts vortex stretching or pressure torque, a variety of interesting flow phenomena arise: meandering currents, topographic waves, frictional currents slowly moving into deeper water, a western boundary current crossing latitude circles. Observations of slope currents are first briefly reviewed in this article, then the different possible vorticity balances are discussed in turn and related to observation where possible. The unifying thread is that vortex stretching is present and important in all of the phenomena discussed.

In press: Advances in Geophysics.

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WHOI Contribution No. 6480.

## CIRCULATION OF SLOPEWATER

G. T. Csanady and P. Hamilton

The recently conducted Mid-Atlantic Slope and Rise (MASAR) experiment yielded much new information on the structure and behavior of slopewater, the water mass occupying the upper "Slope Sea", a narrow band of ocean between the Gulf Stream and the continental shelf from Cape Hatteras to the Grand Banks. The results of this experiment, combined with earlier evidence, have been used to construct a new empirical schema of slopewater circulation. Key features are:

(1) Inflow of Coastal Labrador Sea Water (CLSW) across the Grand Banks at the rate of $4 \cdot 10^6$ m$^3$ s$^{-1}$, and isopycnal advection from the Gulf Stream thermocline at the rate of $6 \cdot 10^6$ m$^3$ s$^{-1}$, the total draining eastward;

(2) A closed cyclonic gyre in the western Slope Sea, transporting approximately $3 \cdot 10^6$ m$^3$ s$^{-1}$ along the New Jersey coast southward; and

(3) Seasonal formation of a pycnostad by convective overturn and its flushing in approximately 6 months.

Some of the CLSW inflow retroflects and turns eastward following entry into the Slope Sea, but a significant fraction flows westward along the coast and rounds the western gyre before draining eastward.

The circulation just described reaches to an approximate depth of 500 m. Deeper layers move through the Slope Sea southwestward. The layers of the Gulf Stream thermocline in contact with slopewater along isopycnals encompass the Antarctic Intermediate Water (AAIW) core, as well as the nutrient maximum and oxygen minimum layers. Shoreward advection of these layers and seasonal overturn to 200 m establish conditions favoring productivity in the upper slopewater, as well as on the shelf.

In press: Continental Shelf Research.

Supported by: DoE Contract DE-AC0279EV10005 and Mineral Management Service Agreement.

WHOI Contribution No. 6483.

## THE RESPONSE OF STRATIFIED SHELF AND SLOPE WATERS TO STEADY OFFSHORE FORCING

Kathryn A. Kelly and David C. Chapman

The effect of steady, deep ocean pressure forcing on the flow over a continental slope and shelf region is examined using a linear and time-independent numerical model which includes continuous stratification, vertical and horizontal diffusion of momentum and density and linear bottom friction. The penetration of the pressure forcing is measured by the vertically averaged kinetic and potential energy as a function of cross-shore location. The most important factor governing the penetration of energy across the continental slope is the vertical structure of the imposed forcing: a shallow pressure perturbation can penetrate easily onto the upper slope. Increasing the stratification also increases the energy penetration but not as effectively. Diffusion is relatively unimportant. The velocity field over the continental shelf is depth independent regardless of the stratification or the location or vertical structure of the forcing function and relatively little energy penetrates beyond the shelf break.

In press: Journal of Physical Oceanography.

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WHOI Contribution No. 6555.

## A HEAT BUDGET FOR THE NORTHERN CALIFORNIA SHELF DURING CODE-2

Steven J. Lentz

Moored current, water temperature, and meteorological observations made during the summer of 1982 as part of CODE-2 are used to study both the mean and fluctuating heat budget for the northern California shelf. The volume considered extends from the sea surface to the bottom, from the coast to near the shelf break (13 to 23 km offshore), and 56 km alongshore. The largest terms in the mean heat budget over a 105 day period spanning the summer season were a surface heat flux of $1.6 \times 10^{11}$ W into the ocean and an offshore heat flux of $2.4 \times 10^{11}$ W due primarily to an offshore flow of relatively warm water in the upper 30 m. Cooling due to an alongshore heat flux divergence is $0.6 \times 10^{11}$ W. Fluctuations with time scales from days to weeks are large relative to the means. The correlation between observed changes in the heat content of the volume and the changes predicted by estimating the heat fluxes into and out of the volume is 0.82. The primary balance in the fluctuating heat budget is heating and cooling of the volume in response to on/offshore fluxes of heat in the upper 30 m. A simple two-dimensional Ekman model reproduces the major features of the

observed offshore heat flux, correlation 0.82, indicating that this offshore heat flux is wind-driven and is characteristic of upwelling. However, at alongshore scales less than 56 km there is considerable alongshore variability in the the cross-shelf heat flux presumably due to eddy motions, particularly over the outer shelf. Standard deviations of the alongshore heat flux are about 50% of the cross-shelf heat flux. Two modes of alongshore heat flux variability are observed. Over the outer shelf large equatorward heat fluxes are observed during the early part of the upwelling season. This model is associated with strong vertical shears in alongshore velocity in the vicinity of the upwelling front which results equatorward flow of the warm surface water relative to the colder deep water. The second mode of alongshore heat flux variability is concern-treated over the inner shelf an related to the wind such that poleward heat fluxes occur in the northern portion of the volume during wind relaxations (periods of weak winds). The presence of an anomalous lens of warm water over the shelf during CODE-2 is also examined.

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WHOI Contribution No. 6521.

## HYDRAULIC CONTROL OF FLOWS WITH NONUNIFORM POTENTIAL VORTICITY

Lawrence Pratt and Laurence Armi

The hydraulics of flow contained in a channel and having nonuniform potential vorticity is considered from a general standpoint. The channel cross-section is rectangular and the potential vorticity is assumed to be prescribed in terms of the stream function. We show that the general computational problem can be expressed in two traditional forms; the first of which consists of an algebraic relation between the channel geometry and a single dependent flow variable. The second consists of a pair of quasilinear differential equations relating the geometry to two dependent flow variables. From these forms we derive a general "branch condition" indicating a merger of different solutions having the same flow rate and energy and show that this condition implies that the flow is critical with respect to a certain long wave. It is shown that critical flow can occur only at the sill in a channel of constant width and (with one exception) at a point of width extremum in a flat bottom channel. We also discuss the situation in which the fluid becomes detached from one of the side walls.

An example is given in which the potential vorticity is a linear function of the stream function and the rotation rate is zero, a case which can be solved analytically. When the potential vorticity gradient points left (facing downstream), allowing propagation of potential vorticity waves against the flow, multiple pairs of steady states are possible, each having a unique modal structure. Critical control of the higher mode solution is primarily over vorticity, rather than depth. Flow reversals arise in some situations, possibly invalidating the prescription of potential vorticity.

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WHOI Contribution No. 6479.

## TOPOGRAPHIC WAVES OVER THE CONTINENTAL SLOPE

Ping-Tung Shaw and G. T. Csanady

Current meter data taken during a one-year period over the continental slope and upper rise in three cross-isobath sections are examined for energy distribution, coherence, and phase propagation of topographic waves. A peak at 15 days is present in the energy preserving spectrum of the near-bottom currents on the rise and slope. The rotary spectrum shows that there is only one wave component at this period. The phase of this wave is consistent with that of an offshore propagating topographic wave. Therefore, motion on the upper rise and lower slope is dominated by topographic waves. Onshore energy flux associated with these waves is blocked by the continental slope, and wave rays turn toward the direction of isobaths. Waves south of Cape Cod and those off Chesapeake Bay may be generated by sources from different section of the Gulf Stream.

Supported by: DoE Contract DE-AC0279EV10005 and National Science Council of China Contract NSC750209-M002a-10.

WHOI Contribution No. 6523.

## INSTRUMENTATION AND EXPERIMENTAL METHODOLOGY

### CHARACTERIZATION OF THE PATTERNS OF DIEL MIGRATION USING A DOPPLER SONAR

Albert J. Plueddemann and
Robert Pinkel

Measurements of backscattered intensity and Doppler velocity are made over a depth interval of 60 to 1200 m using a 67 kHz Doppler sonar mounted on the Research Platform FLIP. Data are analyzed for a 13 day period during which FLIP drifted over a distance of approximately 115 km. The existence of vertically migrating layers is evident in both the intensity and vertical velocity fields. Analysis of the temporal variations of intensity and vertical velocity from a long-term mean state provide complementary characterizations of migration patterns. Three distinct scattering layers are observed with daytime depths of about 300, 560, and 1000 m. Both intensity and velocity data are consistent with vertical migration rates of between 1.0 an 4.0 cm $s^{-1}$. The patterns of vertical migration of the three layers show a high degree of persistence over a time period of 13 days and horizontal scales of order 50 km. Day-to-night (12 hr) differences in profiles of backscattered intensity are found to be significant compared to difference between successive days or successive nights, confirming a day-to-night re-distribution of scatterers. Day-to-day (24 hr) variability in the intensity and velocity fields is generally small compared to the magnitude of the anomalies defining the scattering layers. The exception is an isolated region of high variability between 100 an 250 m depth during daylight hours which is associated with a relative minimum in backscattered intensity.

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WHOI Contribution No. 6649.

### THE DEVELOPMENT OF A FINE- AND MICRO-STRUCTURE PROFILER

Raymond W., Schmitt, John M. Toole,
Richard L. Koehler, Edward C. Mellinger
and Kenneth W. Doherty

A new freely-falling profiler for the measurement of finescale variations in temperature, salinity and horizontal velocity and microscale variations in temperature, conductivity, velocity and refractive index has been constructed. The profiler features include: full ocean depth capability, an on-board microcomputer for the control of sampling, data storage and operations, four megabytes of solid state mass storage, and commercially available sensors. Because the data are transferred electronically to a microcomputer for archiving, the instrument can be redeployed after use without opening the pressure case. Twenty to forty drops may be done before the battery needs to be replaced. Several different sensor configurations are possible, depending on the type of small-scale mixing process (shear instability, double-diffusive convection) that is of interest. By observing both fine-structure and micro-structure with one instrument, it is possible to study the relationship between the finescale driving forces an the small scale mixing events. Only by clearly establishing these connections will it be possible to assess the role of the dissipative processes in the ocean and model their effects on the large scale property distributions.

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## OCEAN CIRCULATION AND LOW FREQUENCY VARIABILITY

### EDDY MOMENTUM AND HEAT FLUXES AND THEIR EFFECTS ON THE CIRCULATION OF THE EQUATORIAL PACIFIC OCEAN

Harry L. Bryden, Esther C. Brady and
David Halpern

Eddy momentum and heat fluxes are estimated from three-dimensional arrays of long-time series current meter measurements in the equatorial Pacific near 152°W and 110°W during 1979 to 1981. Eddies transport eastward momentum away from the equator above the core of the Equatorial Undercurrent; they transport eastward momentum the equator below the Undercurrent core. The vertical integral of the eddy

momentum flux divergence is equivalent to a westward wind stress of 0.16 dyne $cm^{-2}$. Eddies transport heat toward the equator at all depths down to 250 m. At 100 m depth and below, the eddy heat flux convergences are remarkably similar at 152°W and 110°W. Above 100 m, the heat flux convergence at 110°W is much larger than that at 152°W. The vertical integral of the average eddy heat flux convergence between 152°W and 110°W is equivalent to a heating of the equatorial region at a rate of 245 W $m^{-2}$. Lateral eddy viscosities and diffusivities are of order 0.5 to 5 x $10^7$ $cm^2$ $s^{-1}$, similar to those generally used in numerical models. Eddy coefficients, however, are positive only above the core of the Equatorial Undercurrent and are consistently negative below the Undercurrent core. Fluctuations with periods between 32 and 13 days and centered at a 21-day period contribute the bulk of the eddy heat and momentum fluxes.

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WHOI Contribution No. 6519.

## OCEAN HEAT TRANSPORT ACROSS 24°N IN THE PACIFIC

Harry L. Bryden, Dean H. Roemmich and John A. Church

Ocean heat transport in the North Pacific is estimated to be 0.85 x $10^{15}$ W northward from the 1985 transpacific hydrographic section across 24°N. Previous estimates of North Pacific heat transport at subtropical latitudes had ranged between 1.14 x $10^{15}$ W northward and 1.17 x $10^{15}$ W southward. The error in this new direct estimate of Pacific heat transport is approximately 0.25 x $10^{15}$ W. In addition, it is suggested that the annual variation in poleward heat transport across 24°N in the Pacific is of order 0.2 x $10^{15}$ W, as long as the deep circulation below 1000 m exhibits little annual variation in water mass transport. Together, the Pacific and Atlantic transoceanic sections essentially close off the global ocean north of 24°N so that the total ocean heat transport across 24°N is estimated to be 2.1 x $10^{15}$ W northward. This ocean heat transport is larger than the northward atmospheric energy transport across 24°N of 1.7 x $10^{15}$ W. The ocean and atmosphere together transport 3.8 x $10^{15}$ W of heat across 24°N, which is in reasonable agreement with classic values of 4.0 x $10^{15}$ W derived from consideration of the earth's radiation budget but which is markedly less than the 5.3 x $10^{15}$ W required by recent satellite radiation budget determinations.

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WHOI Contribution No. 6570.

## ON LARGE-SCALE CROSS EQUATORIAL FLOW IN THE PACIFIC OCEAN

Terrence M. Joyce

A scheme for calculation of cross-equatorial flow is presented which permits an estimation of meridional velocity at the equator from hydrographic station data and surface wind stress. It is offered to rationalize the observations that surface winds are neither zonal nor spatially uniform at the equator and that large-scale patterns exist in the meridional slope of the dynamic height field at the equator. Using historical data in the equatorial Pacific for surface wind stress and dynamic height, a large-scale estimate of meridional velocity is presented for the upper 2000 m with a zonal resolution of 10° of longitude. Across much of the central equatorial Pacific the flow is northward in the upper 200 m and southward at greater depth. Southward near surface currents are estimated east of 120°W in agreement with direct current measurements at 110°W. The frictional component to the flow, though determined only in the vertically integrated sense, is included assuming an exponential decay from the surface. Over much of the basin the pattern of northward surface, southward sub-surface flow is responsible for an overall net positive heat transport across the equatorial Pacific Ocean.

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## ON THE WIND-DRIVEN CROSS EQUATORIAL FLOW IN THE ATLANTIC

Terrence M. Joyce

The zonally-integrated curl of the wind stress across the equatorial Atlantic Ocean results in a southward transport of 10 x $10^6$ $m^3/s$ of water into the South Atlantic which must be returned in a western boundary current. Historical, climatological hydrographic and wind data have been used together with a simple steady model to calculate the vertical and horizontal structure of the southward Sverdup transport. In contrast to the Pacific Ocean, the meridional currents are southward over most of

the equatorial Atlantic with strongest flow in the central Atlantic near the surface; the major exception to this pattern is between 31-39° W where near surface currents are northward. Estimates of the meridional heat transport associated with this steady, wind-driven circulation are .6-.8 x $10^{15}$W. Climatological data also reveal an extraordinary correlation (0.86) between seasonally varying meridional wind stress and meridional sea surface slope in the central and eastern equatorial Atlantic, as if the ocean were responding in a quasi-steady manner to the seasonal changes in the winds.

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WHOI Contribution No. 6640.

## ZONAL VELOCITY STRUCTURE AND TRANSPORT IN THE KUROSHIO EXTENSION

Terrence M. Joyce and William J. Schmitz

The meridional structure of the zonal flow in the Kuroshio Extension is investigated using a combination of data from hydrographic sections and moored current meter arrays. We emphasize 165°E between 30 - 42°N, where high quality and very stable current measurements at 150 and 400 m extend over a two year period from October of 1983 to October 1985. Hydrographic (CTD/$O_2$) sections were occupied during the initial deployment and a second time when the array of six moorings was reset in 1984. The deep currents were extremely stable from one year to the next and revealed a pattern of weak eastward flow at 400 m under the axis of the Kuroshio extension, with strong westward flow on either flank. When combined with the hydrographic data, the total transport of the eastward flowing Kuroshio Extension was estimated to be 5.70 $\pm$ 3.7 Sv., essentially the same as when referenced to the bottom (57.0 $\pm$ 2.0). South of 34°N, the velocities were westward at all levels, with a net transport of -72 Sv.; north of 37°N the flow in the upper km was eastward near the axis of the Oyashio, or subarctic front, ad westward elsewhere, yielding a net transport of -44 Sv. The net transport across the entire section was westward and equal to -62.7 $\pm$ 12.3 Sv., compared to 31 $\pm$ 15 Sv. when referenced to the bottom.

New methods of estimating transport when combining direct current and hydrographic data are illustrated, where compatibility between dynamic height estimates is required. Observations of dynamic height variability across 165°E array using the current meters suggested that the mean currents at 4000 m were consistent with the dynamic height range observed hydrographically. However, the yearly-averaged velocities at 150 m under-sampled the eastward upper level flow. Results are also compared to previously published work at 152°E and with new data at 175°W. At 152°E, previous estimates of zonal transport over a similar latitude range yield -31 $\pm$ 16 Sv. when current meter and hydrographic data were combined; our study suggests -31 $\pm$ 31 Sv. The section-averaged zonal transport changes sign across the Emperor Seamounts, becoming positive at 175°W, where the hydrographic data and yearly averaged array data are totally consistent.

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WHOI Contribution No. 6700

## WHERE DOES THE AMAZON WATER GO?

Frank E. Muller-Karger, Charles R. McClain and Philip L. Richardson

Historical shipdrifts in the tropical Atlantic show a continuous current extending from the eastern tip of Brazil into the Caribbean Sea. Yet Amazon River water has been observes several hundred kilometers off the coasts of Brazil and the Guyanas. How does the Amazon water move offshore? New information obtained with the Coastal Zone Color Scanner and with drifting buoys reveals that the discharge of the Amazon is carried around a retroflection of the North Brazil Current and into the North Equatorial Countercurrent between June and January each year. From about February to May the Countercurrent and the retroflection weaken or banish, and Amazon water flows northwestward.

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WHOI Contribution No. 6571.

## A NINE-YEAR TRAJECTORY OF A SOFAR FLOAT IN THE SOUTHWESTERN NORTH ATLANTIC

W. B. Owens, P. L. Richardson, W. J. Schmitz, Jr.., H. T. Rossby and D. C. Webb

A SOFAR float near a depth of 1000 m was tracked intermittently for nine-years, the longest such trajectory every obtained. This instrument was launched near 24°N, 69°W in October 1976 and tracking ceased with it was near 23°N, 56°W in May 1984. The long term drift is ~1 cm $s^{-1}$ eastward in agreement with a few other 700 m

floats and with geostrophic flow estimates for this region. The kinetic energy level of 20 $cm^2s^{-2}$ is similar to those observed by current meters in the ocean interior away from western boundary currents. The frequency distribution of eddy variability is more "peaked" at the mesoscale than Eulerian spectra for the same energy levels, and the zonal and meridional variances are roughly the same.

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WHOI Contribution No. 6648.

## GULF STREAM VELOCITY STRUCTURE THROUGH INVERSION OF HYDROGRAPHIC AND ACOUSTIC DOPPLER DATA

Stephen D. Pierce and Terrence M. Joyce

Near-surface velocities from a shipborne acoustic Doppler instrument are used together with CTD/$O_2$ data to make estimates of geostrophic velocities off of Cape Hatteras. The data set consists of two transects across the Gulf Stream at approximately 73°W and 71°W made by the R/V ENDEAVOR in August 1982. An inversion technique is applied which makes use of both the acoustic Doppler data and property conservation requirements. The method produces estimates of the absolute flow field across the two sections with formal errors of 1-2 cm/s. At the time of the observations, the net Gulf Stream transports are estimated to be $116\pm2 \times 10^9$kg/s at 73°W and $161\pm4 \times 1-^9$kg/s at 71°W. A southwestward Deep Western Boundary Current transport is estimated at $4\pm1 \times 10^9$kg/s. Taken together with recent Gulf Stream transport estimates of similar accuracy made in June 1982, the results are in general larger than historical transport estimates in this region.

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WHOI Contribution No. 6569.

## SUSPENDED PARTICULATE MATTER TRANSPORT THROUGH THE VEMA CHANNEL

M. J. Richardson, P. E. Biscaye, W. D. Gardner and N. G. Hogg

Sixteen-month time-series measurements of water velocity and light scattering were coupled with hydrographic and suspended particulate matter sections to determine the flux and the variability in flux of suspended particulate matter through the Vema Channel. The northward flux of SPM through the Vema Channel ranged from 3 to $10.5 \times 10^4$ g $s^{-1}$ with a mean of $6.5 \times 10^4$ g $s^{-1}$. The largest fluxes were measured in the deepest and eastern portions of the channel with maximum fluxes of suspended particulate matter at specific sites being roughly two to four times the mean flux.

Some of the suspended particulate matter in the channel may be eroded from the channel itself by the swift currents or eddy-like features, however, the known manganese encrustation and hard floor of the channel suggest that the deep channel floor is not a likely source of sediment. A primary source of the suspended particulate matter in the channel may be the sediment drifts in the Argentine Basin with their associated high standing crops of resuspended particulate matter. This resuspended material would then be transported by the Antarctic Bottom Water into and through the Vema Channel into the Brazil Basin. The northward flux of suspended particulate matter through the Vema Channel is presently a significant, but not dominant, influence on sedimentation in the Brazil Basin.

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WHOI Contribution No. 6503.

## THE COLUMBUS LANDFALL: VOYAGE AND TRACK CORRECTED FOR WINDS AND CURRENTS

Philip L. Richardson and Roger A. Goldsmith

Columbus's first landfall in the new world is still in considerable debate. In order to help resolve its identify, we have reconstructed and plotted Columbus's first voyage by using his logged courses and distances on the SANTA MARIA and by carefully applying corrections using historical winds (leeway) and currents (set and drift). The most significant finding is that when winds and currents are accounted for, the end of the voyage lies very close to San Salvador Island. No adjustments were applied (or needed) to increase or decrease the cruise track length to match a possible first landfall as all other investigators have done. The effect of wind and current on the latitude of the endpoint is rather small-wind shifts the cruise endpoint northwestward around 8 kilometers; current shifts it westward 135 kilometers. These findings differ significantly from recent results presented by

Luis Marden (National Geographic, 170, 572-577, 1986) who concluded the voyage ended at Samana Cay. Marden was the first person to adjust the track for leeway and currents, but he applied leeway on only the first part of the voyage in the Northeast Trades, omitting leeway on the second part in the Southeast Trades, and he used currents given on the Pilot Charts which are three times faster than the appropriate vector-averaged velocities. The largest uncertainty in the cruise endpoint is due to the poorly known magnetic variation for 1492.

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WHOI Contribution No. 6561.

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## EXPLORATION OF THE EDDY FIELD IN THE MID-LATITUDE NORTH PACIFIC

William J. Schmitz, Jr..

Fourteen moorings were deployed across the mid-latitude North Pacific from 165E to 152W, for approximately 2 years during 1983-1985. Ten mooring sites had previously been occupied at similar latitudes (30-40N nominal) for roughly two years (1980-1982) along 152E. Taken together, these observations form the basis for the first systematic basin-wide zonal exploration of the eddy field based on moored instrument techniques in the mid-latitude North Pacific along the Kuroshio Extension System and North Pacific drift. Eddy kinetic energy ($K_E$) at abyssal depths decays sharply moving east from 152E, dropping a factor of 4 by 165E. There is a plateau in abyssal $K_E$ of about 10 $cm^2\ s^{-2}$ across the Emperor Seamounts from 165 to 173E. Abyssal $K_E$ drops to roughly 5 $cm^2\ s^{-2}$ at 175 W and 1 $cm^2\ s^{-2}$ at 152W, for a total decay of about a factor of about 50 across the mid-latitude North Pacific. Upper level $K_E$ decreases by a total of roughly two orders of magnitude (approximately $10^3$ to $10^1$) from 152E to 152W.

The most energetic sites at 152E and 165E have essentially the same vertical structure (shape), with the deep and near surface amplitudes being 4 and 3 times respectively higher at 152E. In fact, the same type of vertical profile for $K_E$ is appropriate as a first approximation across the entire mid-latitude North Pacific, with amplitudes generally decreasing eastward and away from the Kuroshio Extension. Distributions of $K_E$ with frequency are typically peaked somewhat at the mesoscale near the Kuroshio Extension, and generally become more "red" going east and/or toward lower energy areas, although examples of essentially every type of partitioning are available. $K_E$ values at 165E are generally the most stable from year-to-year so far measured in energetic regions of the open ocean, at all depths.

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WHOI Contribution No. 6500

## RECENT SOFAR FLOAT AND MOORED CURRENT METER OBSERVATIONS IN THE EASTERN ATLANTIC NEAR 32N

William J. Schmitz, Jr., Philip L. Richardson and James F. Price

Basic flow statistics from the two-year deployment of a mooring in the vicinity of 32N and 24W are presented, along with intercomparisons between analogous SOFAR float results concurrent with the first year of moored instrument data. Current-temperature meters were deployed in the main thermocline (~500 m depth), in Mediterranean Water (1000-1100 m depth) along with the SOFAR floats, and at an abyssal (~ 3000 m) level. The float and current meter averages over a common time interval are at least roughly the same, with eddy field intercomparisons being better than those for mean flow.

Strong year-to-year variability in the time-averaged flow and eddy statistics at thermocline depths is observed. The two-year based eddy kinetic energies ($K_E$) are about the same as found using a variety of data taken nearby, whereas zonal mean speeds exhibit strong, comparatively short horizontal scale variability. It is pointed out that all measurements available exhibit a significant (perhaps dominant) but relatively unexplored interannual variability, not yet explicitly connected to variations in the gyre-scale circulation. Frequency distributions of $K_E$ are peaked at the (temporal) mesoscale at abyssal depth, and $K_E$ increases with increasing period in the thermocline. The distribution of $K_E$ with frequency at thermocline depths is also temporally inhomogeneous, although not at mesoscale and shorter periods. Meridional frequency distributions of $K_E$ are peaked at the mesoscale and zonal distributions are more "red". The eddy field characteristics at this site are shown to be similar to those from other low energy regions in the North Atlantic and the North Pacific.

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WHOI Contribution No. 6499.

## ON THE CIRCULATION OF THE UPPER WATERS IN THE WESTERN EQUATORIAL PACIFIC OCEAN

J. M. Toole, E. Zou, and R. C. Millard

Historical hydrographic data and CTD/$O_2$ observations obtained on two recent cruises are used to investigate the circulation of the upper waters of the western equatorial Pacific Ocean. The study area lies between 20°N and the land boundary of the Papua-New Guinea-Solomon Island coasts, 170°E and the Philippine coast. Seasonal mean and annual averaged sections are constructed from the historical data set to address the strength of the major equatorial currents and the water mass budget of the far western region of the study area. We find indication of significant contribution of southern hemisphere waters to the North Equatorial Countercurrent with an inferred Pacific to Indian Ocean throughflow of Mindanao Current waters of order 1 Sv. The recent observations, acquired under the auspicious of the United States/People's Republic of China cooperative program, were collected in January-February and November to December 1986. The thermohaline structure of the various currents and net transports estimated for the 1986 data sets are examined and compared with the historical mean data. Large differences are seen between the two modern sections obtained along 165°E. These reflect high frequency variability (as demonstrated by comparison with a third section obtained two weeks prior to the January-February cruise) and interannual variability (the second of the cruises occurred during the onset of the 1986/87 El Nino event).

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Contribution No. 6553.

## DEEP CURRENT IN THE CENTRAL SUBARCTIC PACIFIC OCEAN

Bruce A. Warren and W. Brechner Owens

Sections of closely spaced CTD stations along Longs. 165°W, 175°W, and 175°E, in combination with 14-month current records from the central longitude, define two deep, nearly zonal currents, with speed increasing upward, in the subarctic Pacific. One flows eastward above the Aleutian Rise and Aleutian Trench, and appears to be a concentration of geostrophic flow forced by the bottom topography. The other flows westward along the Aleutian Island ridge, and is the northern-boundary current predicted by deep-circulation theory. Both currents reach to the sea surface, the boundary current being simply a deep extension of the Alaskan Stream. The current records were too few to permit better than rough estimates of volume transports, but to the extent that they could be combined with thermal-wind calculations they suggest, at Long. 175°W, (1) a transport of 28 x $10^6$ $m^3$ $s^{-1}$ for the Alaskan Stream, of which 5 x $10^6$ $m^3$ $s^{-1}$ was found below 1500 m, and (2) a transport of around 20 x $10^6$ $m^3$ $s^{-1}$ for the eastward jet, of which 5-10 x $10^6$ $m^3$ $s^{-1}$ was estimated below 1500 m.

The deep water in the area surveyed was so nearly homogeneous that salinity, oxygen, and nutrients could generally be calculated from potential temperature within measurement error; these additional properties were therefore of only limited use in tracing the deep flow. However, temperature maps at 2 and 4 km demonstrate continuity of the two deep currents across the 60° of longitude between Japan and the Gulf of Alaska. The eastward jet can be tracked back through the Emperor Seamount chain to the Zenkevich Rise off Japan, while the deep Alaskan Stream can be followed downstream to Long. 180°, where it separates from the boundary and flows due westward to the Emperor Seamount chain, which it rounds to the north on its way to flowing southward as the deep western boundary current of the subarctic Pacific. Other details of the water-property fields are described in the text, and comparisons are made with the deep subpolar boundary flow of the North Atlantic.

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WHOI Contribution No. 6616.

# THEORETICAL AND LABORATORY MODELS

## FINITE-AMPLITUDE EVOLUTION OF TWO-LAYER GEOSTROPHIC VORTICES

Karl R. Helfrich and Uwe Send

The finite-amplitude evolution of circular two-layer quasigeostrophic vortices with piecewise uniform potential vorticity in each layer (also termed "heton" clouds by Hogg and Stommel (1985a) and Pedlosky (1985)) is studied using the contour dynamics method. The numerical investigations are preceded by a linear stability analysis

which shows the stabilizing influence of deepening the lower layer. Net barotropic flow may be either stabilizing or destabilizing. The contour dynamics calculations for baroclinic vortices show that supercritical conditions may lead to explosive break up of the vortex via the generation of continuous hetons at the cloud boundary. The number of vortex pairs is equal to the azimuthal mode number of the initial disturbance. An additional weakly supercritical regime in which amplitude vacillation, but not explosive growth, occurs is identified. Vortices with net barotropic circulation behave similarly except that the layer with vorticity of sign opposite of the barotropic circulation will break up first. Strong barotropic circulation can inhibit the development of hetons. The stronger layer may eject thin filaments, but remain mostly intact. Calculations for initial conditions composed of several unstable modes show that the linearly most unstable mode dominates at finite-amplitude.

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WHOI Contribution No. 6673.

## A THREE-LAYER MODEL FOR WIND-DRIVEN CIRCULATION IN A SUBTROPICAL-SUBPOLAR BASIN PART III. POTENTIAL VORTICITY ANALYSIS

Rui Xin Huang

Recent progress in thermocline theory is linked and demonstrated by a wind-driven three-layer numerical model. The dynamic balances of the circulation of the model are studied through examination of potential vorticity budgets. Potential vorticity balances of two cases of the subcritical state have been calculated over the entire basin and along trajectories. Vorticity budget analysis clearly shows several zones of different dynamics in the gyre scale circulation. High potential vorticity water masses in the subtropical western boundary region are shown to be created by strong lateral momentum mixing and bottom friction implemented in the model. These water masses move into the subtropical gyre interior in the form of high potential vorticity tongues. Within the gyre interior the potential vorticity of the water parcels can be either quasi-onservative (within a regime of weak forcing/diffusion) or slowly modified by local forcing/diffusion. The potential vorticity dynamics in the subpolar gyre shows a similar feature but generally with a different sign for the source/sink terms. Along-trajectory analysis of a case of the supercritical state shows clearly four zones of different potential vorticity dynamics, i.e. the frontal zone, the outcropping zone, the subduction zone, and the western boundary zone. These concrete numerical examples illustrate the dynamics of the fundamental regimes in the gyre-scale circulation as discussed in the recently proposed theories of thermocline.

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WHOI Contribution No. 6524.

## IDEAL FLUID THERMOCLINE WITH WEAKLY CONVECTIVE ADJUSTMENT IN A SUBPOLAR BASIN

Rui Xin Huang

The ideal fluid thermocline equation is extended to include a weakly convective adjustment process taking place in a subpolar basin. The convective adjustment creates a density-homogenized layer on top of a moving unventilated thermocline whose potential vorticity is specified as a given boundary condition. Convective adjustment makes the moving water stratum shallower and the current more surface-intensified.

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WHOI Contribution No. 6482.

## NOTES ON BOUNDARY VALUE PROBLEMS OF THE IDEAL FLUID THERMOCLINE

Rui Xin Huang

Boundary value problems are formulated for the ideal fluid thermocline with continuous stratification. Ekman pumping and surface density are specified as the upper boundary conditions. No flow is permitted through the ocean's eastern boundary nor its bottom. Each water column is divided into three parts, i.e., the stagnant abyssal water, the unventilated thermocline with its potential vorticity specified a priori, and the ventilated thermocline with its potential vorticity determined by a global dynamic balance.

Numerical integration of the ideal fluid thermocline equations is reduced to repeatedly integrating a second-order ordinary differential equation at each station. Our approach parallels some earlier models,

i.e. Luyten et al. (1983), Pedlosky and Young (1983), and Huang (1986). This integration process reveals the nonlinear interaction between the ventilated and unventilated thermocline and sheds light on the long-pursued question of how the potential vorticity field is determined in the ventilated thermocline of a continuously stratified ocean.

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WHOI Contribution No. 6636.

## ON THE GENERALIZED EASTERN BOUNDARY CONDITIONS AND THE THREE-DIMENSIONAL STRUCTURE OF THE IDEAL FLUID THERMOCLINE

Rui Xin Huang

A generalized eastern boundary condition of no-net-zonal-flux is applied to the ideal fluid thermocline with continuous stratification. Assuming that the effect of mixing can allow a vertical exchange of water mass at the eastern boundary, it is found that if the Ekman pumping velocity is everywhere negative within the subtropical basin, the only possible mode of this type of water mass exchange is a first baroclinic mode with the upper layer water moving into the eastern boundary and the lower layer water coming into the interior.

The structure of the eastern boundary is an inseparabale part of the entire solution and thus cannot be determined in isolation. Relaxing the strictly no-zonal-flux eastern boundary condition releases the unnecessary kinematic constraint over the upper surface density gradient near the northern boundary of the subtropical gyre and gives rise to the vast zone of the boundary ventilated thermocline next to the eastern boundary, thus making the ideal fluid thermocline solution more realistic.

Supported by NSF Grant OCE85-14771.

WHOI Contribution No. 6638.

## AN INERTIAL THEORY OF THE EQUATORIAL UNDERCURRENT

Joseph Pedlosky

An inertial non-linear model of the equatorial undercurrent is presented. The model is a simple two-layer model whose lower layer represents the undercurrent. The flow in the lower layer preserves potential vorticity and Bernoulli function. The former includes the relative vorticity of the current and latter includes the current's kinetic energy. The required relation between the potential vorticity and the Bernoulli function is determined by matching the solution far from the equator with the Ventilated Thermocline theory of Luyten et al. (1983).

The model describes an eastward accelerating undercurrent fed by a general wedge-shaped meridional circulation pattern. The general character of the meridional and zonal flow, as well as the magnitudes of the undercurrent velocity, the current width and thermocline depth agree reasonably well with observations.

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WHOI Contribution No. 6485.

## ENTRAINMENT AND THE TERMINATION OF THE EQUATORIAL UNDERCURRENT

Joseph Pedlosky

An ideal fluid model of the Equatorial Undercurrent is modified by the addition of a specified, cross-isopycnal entrainment of fluid into the upper mixed layer. The entrainment is limited to a narrow region straddling the equator. It is shown how this entrainment serves to modify the value of the Bernoulli function along the equator.

For cases in which the Bernoulli function is rendered constant along the eastern boundary, the transport in the undercurrent is completely exhausted by the time the current reaches the eastern wall. The transport of the current is transferred to the upper mixed layer where it exits poleward. It is suggested that the gradual bleeding by entrainment rather than inertial collision is responsible for the eastern termination of the undercurrent.

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WHOI Contribution No. 6701.

## ENTRAINMENT AND HOMOGENIZATION OF A PASSIVE TRACER IN A NUMERICAL MODEL GYRE

Robert S. Pickart

The basic mechanism by which tracer is entrained into a spatially decaying gyre from an external source is examined, as well as the homogenization which subsequently occurs. A simple advective-

diffusive numerical model is used whose streamlines consist of an elongated gyre situated beside a (distinct) boundary current, which inputs tracer into the domain. (This is meant to represent the deep cyclonic recirculation of the Gulf Stream and adjacent deep western boundary current.) An accompanying shear flow analysis shows that two parameters dictate the manner in which tracer penetrates across streamlines of the gyre: a peclet number and a parameter which measures the strength of the cross-stream shear. The large values of these parameters causes a plume of tracer to spiral inward towards the center of the gyre. In the steady state, the tracer which has accumulated in the center of the gyre becomes homogenized. The size of this uniform area is related to the extent to which the spiral penetrated the gyre, and decreases with increasing diffusivity, as several examples illustrate.

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## THE EFFECT OF DISSIPATION ON SPATIALLY GROWING BAROCLINIC WAVES

L. M. Polvani and J. Pedlosky

The question of convective (i.e. spatial) instability of baroclinic waves on an f-plane is studied in the context of the two-layer model. The viscous and inviscid marginal curves for linear convective instability are obtained. The finite-amplitude problem shows that when dissipation is O(1) it acts to stabilize the waves that are of Eddy type. For very small dissipation the weakly nonlinear analysis reveals that at low frequencies, contrary to what is known to occur in the temporal problem, in addition to the baroclinic component a barotropic correction to the "mean" flow is generated by the nonlinearities, and spatial equilibrium occurs provided the ratio of shear to mean flow does not exceed some critical value. In the same limit, the slighty dissipative nonlinear dynamics reveals the presence of large spatial vacillations immediately downstream of the source, even if asymptotically (i.e. very far away from the source) the amplitudes are found to reach steady values. No case of period doubling or aperiodic behavior was found. The results obtained seem to be qualitatively independent of the form chosen to model the dissipation.

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## MEANDERING AND EDDY DETACHMENT ACCORDING TO A SIMPLE (LOOKING) PATH EQUATION

L. J. Pratt

Nonlinear meandering and 'pinching off' processes are investigated by solving the path equation

$$\partial \ell / \partial t - 1/2 \, \partial \kappa / \partial x = 0.$$

As shown by Pratt and Stern (1986) this dimensionless equation determines the center line latitude $\ell$ of a slowly-varying, equivalent barotropic, quasigeostrophic, f-plane jet with cusped velocity profile and center line curvature $\kappa = \ell_{xx} / (1 + \ell_x^2)^{3/2}$. A class of exact solutions consisting of steadily propagating meander is found having wave length $2\pi/k$ and amplitude a. The meanders form a wave train which can be single-valued (for $ak < 2.61$) or multi-valued (for $2.61 < ak < 8.30$) with respect to the x (eastward) coordinate. For $ak = 8.30$ grazing contact occurs between neighboring meanders and a type of vortex street is formed. The amplitude-dependent dispersion relation for the meanders shows that phase propagation is eastward with speed that increases with decreasing wave length and/or amplitude, trends observed for Gulf Stream meanders new 72°W by Vasquez and Watts (1985.

Numerical solutions are presented for isolated, single-valued initial disturbances having a characteristic wave number $k_o$ and amplitude $a_o$. When $a_o k_o$ is less than a critical value between 1.5 and 2.0, the disturbance disperses. For larger values of $a_o k_o$, the evolution leads to a 'pinching off' phenomenon in which meanders begin to detach from the main portion of the jet and form roughly elliptical eddies.

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WHOI Contribution No. 6554.

## A GYRE IN A NON-UNIFORMLY HEATED ROTATING FLUID

Kevin G. Speer and John A. Whitehead

Convection in a rotating square basin was studied in a laboratory experiment in which the convection is driven by non-uniform heating from below. This experimental configuration is thought to be analogous to large-scale convection in the ocean, driven by non-uniform heating at the surface. As in the non-rotating case, the upper region shows relatively small temperature variation. With rotation, this region has cyclonic circulation. Fluid

moves from the upper region into the thermal boundary layer near the bottom, and then moves toward and enters the rising region at the warm end of the basin.

In press: Deep-Sea Research.

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WHOI Contribution No. 6481.

## T U R B U L E N C E A N D M I X I N G, F I N E- A N D M I C R O- S C A L E P R O C E S S E S

### OPTICAL MICROSTRUCTURE IN THE THERMOHALINE STAIRCASE EAST OF BARBADOS

Eric Kunze, Albert J. Williams, III and Raymond W. Schmitt

Images of optical microstructure from the ocean thermocline east of Barbados are presented, including examples of turbulence, a shear billow and a diffusively unstable interface. While much of the water column was favorable to salt fingering, particularly the high gradient interfaces in the staircase, the few centimeters wide vertical banding reported in other fingering-favorable parts of the ocean were not observed. Instead, almost horizontal banding appeared wherever conditions were conducive to fingering. The role that vertical shear plays in modifying salt fingers may have to be reconsidered.

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WHOI Contribution No. 6448.

### MIXING IN A THERMOHALINE STAIRCASE

R. W. Schmitt

The field program C-SALT (Caribbean-Sheets and Layers Transects) focused on the strong thermohaline staircase in the western tropical North Atlantic. Large- and small-scale surveys and temporal monitoring found an extensive and persistent sequence of subsurface mixed layers. Good evidence for salt finger activity is found in the thermal microstructure in the interfaces, plumes in the mixed layers, and large scale changes in the temperature and salinity of the layers. Dissipation rates of kinetic energy were lower than expected from the laboratory 4/3 power law, but consistent with a "Stern number"-based flux law, in which the flux is inversely proportional to interface thickness. Observations of thermal microstructure also support a Stern number flux law yield estimates for the vertical salt diffusivity of order $1 \times 10^{-4}$ $^{2}$/s. Very thin interfaces found during an earlier survey suggest that higher diffusivities may transiently occur.

In press: Proceedings of the 19$^{th}$ International Liege Colloquium on Ocean Hydrodynamics, Liege, May 4-78, 1987.

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WHOI Contribution No. 6637.

### C-SALT: AN INVESTIGATION OF THE THERMOHALINE STAIRCASE IN THE WESTERN TROPICAL NORTH ATLANTIC

R. W. Schmitt, H. Perkins, J. D. Boyd and M. C. Stalcup

The Caribbean-Sheets and Layers Transect (C-SALT) field program focused on the "staircase" layering found in the main thermocline when temperature and salinity distributions are favorable for the formation of salt fingers. Large- and small-scale surveys, microstructure studies and temporal monitoring of the layers were carried out in spring and autumn of 1985 in an area east of Barbados in the tropical Atlantic.

The staircase investigated contained about 10 well-mixed layers, 5-30 m thick, separate by thinner interfaces with sharp changes in temperature and salinity. The depth range of the layers coincided with a minimum density ratio. The area of strong steps was $0.5 \times 10^{6}$ km$^{2}$ in the spring and $0.6 \times 10^{6}$ km$^{2}$ in the autumn. Individual layers were laterally coherent over scales of 200-400 km and retained their identify for the eight months between surveys. Layers became warmer, saltier and denser to the north and west, with a heat/salt density ratio of 0.85. This ratio is close to that expected for a vertically divergent salt finger flux. This direct indication of water mass conversion provides striking evidence that salt fingers maintain the staircase and make a major contribution to mixing in the thermocline of the region.

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WHOI Contribution No. 6439.

## U P P E R  O C E A N S,  S U R F A C E  L A Y E R  P R O C E S S E S  A N D  M E T E O R O L O G Y

### UPPER OCEAN RESPONSE TO A HURRICANE

John A. Church, T. M. Joyce and James F. Price

CTD and acoustic Doppler current profiler data showed a strongly asymmetric response of the upper-ocean to the passage of tropical typhoon Gay. Currents with speeds up to 1 $ms^{-1}$, and large vertical shear were observed 80 km to the right of Gay's track. These currents rotated at close to the inertial frequency. To the left of Gay's track, the currents were weaker even though there was a secondary maximum in their magnitude. More than 1.5 inertial periods after the passage of Gay, gradient Richardson numbers as low as 0.08 were observed. Vertical velocities (inertial pumping) of up to 0.0001 $ms^{-1}$ are inferred 80 km to the right of Gay's track; such velocities would displace the thermocline by up to 17 m. There was a weaker secondary maximum in vertical velocity 70 km to the left of Gay's track.

Supported by: NSF Grant OCE84-16197.

WHOI Contribution No. 6674.

### WIND-DRIVEN OCEAN CURRENTS AND EKMAN TRANSPORT

James F. Price, Robert A. Weller and Rebecca R. Schudlich

Oceanographers have long sought to verify the theoretical Ekman transport relation, which predicts that a steady wind stress acting together with the Coriolis force will produce a transport of water to the right of the wind. In situ measurements of wind and ocean currents provide a detailed view of this phenomenon. By separating the wind-driven current from the measured total current and by averaging over a long record, it is found that the observed transport is consistent with theoretical Ekman transport to within about 10 percent. In this case the wind-driven transport is strongly surface trapped, with 95 percent occurring in the upper 25 meters as a result of fair summer weather.

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WHOI Contribution No. 6520.

### OCEAN RESPONSE TO A HURRICANE PART I: OBSERVATIONS

Thomas B. Sanford, Peter G. Black, James R. Haustein, James W. Feeney, George Z. Forristall and James F. Price

The response of the ocean to hurricanes was investigated using aircraft-deployable expendable current profilers (AXCP). The goals were to observe and separate the surface wave and surface mixed layer velocities under the storms and to map the across-track and along-track velocity and temperature response in the mixed layer and thermocline. Custom instrumentation was prepared, including slower falling AXCPs and the AXCP equipment was installed on NOAA WP-3D aircraft. Research flights were made into two 1984 hurricanes: Norbert, in the eastern Pacific off Baja, California (19°N, 109°W), and Josephine, off the east coast of the U.S. (29°N, 72°W). Thirty-one probes were deployed in each hurricane, and about half the ACCPs provided temperature and velocity profiles. Most velocity profiles exhibited strong surface wave contributions, slab-like velocities in the SML, strong shears beneath the SML, and only weak flows in the upper thermocline. Separation of the surface gravity wave velocities from the steady and inertial motions was obtained by fitting the profiles to steady flows and shears in three layers and to a single surface wave at all levels. The velocity profiles displayed large divergences to the horizontal SML velocities in the wake of the hurricanes. The observations show a strong enhancement of SML velocities to the right of the storm as expected from numerical simulations. The largest SML velocities were 1.1 m $s^{-1}$ in Norbert and 0.73 m $s^{-1}$ in Josephine. Numerical simulations will be compared with the observations in Part II.

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WHOI Contribution No. 6575.

## LANGMUIR CIRCULATION WITHIN THE OCEANIC MIXED LAYER

Robert A. Weller and James F. Price

The three-dimensional flow in the mixed layer associated with Langmuir Circulation was studied with a new instrument capable of directly measuring the three components of velocity. Regions of convergent surface flow were located with surface drifters. In these regions the downward vertical and downwind horizontal components of the flow were comparable in size and, at times, in excess of 20 cm $s^{-1}$. This downwind, downwelling flow was jet-like in structure, with the maximum velocity located below the surface. Away from the downwelling regions and in the lower half of the mixed layer below the convergence zones, the flow associated with the Langmuir Cells was an order of magnitude smaller and not well resolved in these experiments. On some occasions, when Langmuir Cells appeared suddenly, they were able to mix the weak near-surface stratification that had formed in response to diurnal heating. They could also maintain large shears in the well-mixed fluid near the surface. They did not, however, penetrate with strength to the base of relict mixed layers observed during summer-like conditions or to the base of deeper, more isothermal, mixed layers observed during stormy conditions.

In press: Deep Sea Research.

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WHOI Contribution No. 6493.

# T E C H N I C A L R E P O R T S

## PROGRAMS FOR COMPUTING PROPERTIES OF COASTAL-TRAPPED WAVES AND WIND-DRIVEN MOTIONS OVER THE CONTINENTAL SHELF AND SLOPE

Kenneth H. Brink and David C. Chapman

Documentation and listings are presented for a sequence of computer programs to be used for problems in continental shelf dynamics. Three of the programs are to be used for computing properties of free and forced coastal-trapped waves. A final program may be used to compute wind-driven fluctuations over the continental shelf and slope. This second edition includes several minor revisions and corrections in the computer code and the documentation.

Supported by: NSF under Grant OCE84-08563.

WHOI Technical Report 87-24.

## XBT OBSERVATIONS BETWEEN 10°N - 10°S IN THE ATLANTIC FROM SHIPS-OF-OPPORTUNITY, COMPLEMENTED BY AXBT SURVEYS

John G. Bruce

A description and listing of 82 XBT sections of 61 stations each from ships-of-opportunity between 10°N-10°S in the Atlantic Ocean from January 1980 to January 1986 is presented. This work was associated with the SEQUAL program. A temperature-depth figure for each section is given with surface temperature, salinity, and $\sigma_t$ and wind data. Complimentary AXBT observations during two 1983 surveys are also presented.

Prepared for: NSF under Grants OCE83-02794 and OCE85-15332.

WHOI Technical Report 87-41.

## DATA TELEMETRY, ASSIMILATION AND OCEAN MODELING SEMI-ANNUAL REPORT FOR THE PERIOD OCTOBER 1, 1986 to APRIL 1, 1987

edited by Daniel E. Frye

The University Research Initiative Program is a cooperative project between Woods Hole Oceanographic Institution, Massachusetts Institute of Technology and Harvard. The objectives of this 5-year Office of Naval Research funded program are to advance the state of the art in ocean data telemetry, interpretation of remotely sensed data from satellite, and numerical modeling of ocean circulation. Ocean data telemetry is being addressed by several development projects whose aim is to reliably transfer data from in situ oceanographic instruments to laboratory computers on the shore. The satellite oceanography group is developing expertise in analyzing, manipulating, displaying and archiving data from all of the major satellite oceanographic sensors. The numerical modeling initiative is working on a family of circulation models which can be connected at their boundaries to cover the important mesoscale and basin wide flow regimes. These ambitious plans are intended to bring new technologies

developed in the communications, electronics, satellite sensing and computer science fields into everyday use in oceanography so that they can be ready for the global science programs planned for the 1990's.

Supported by: ONR under Contract N00014-86-K-0751.

WHOI Technical Report 87-21.

## A FSK TELEMETRY MODULE FOR VECTOR MEASURING CURRENT METER

Paul D. Fucile and James R. Valdes

The EG&G Vector Measuring Current Meter (VMCM) used in mooring work provides a 20 ma Serial ASCII Instrumentation Loop (SAIL) communication system. A projected application of the VMCM's via a Frequency Shift Keying (FSK) link. While an FSK modem can communicate with the VMCM, a problem exists with the general operation of the VMCM. If the VMCM is addressed to dump data, it remains on until the unit is re-addressed. If a failure in the link occurs, then the VMCM stays on in a higher power mode and the batteries will be depleted early.

The insertion of a processing block between the modem and the VMCM provides a way to look at incoming data, qualify it and re-transmit it to the VMCM. The VMCM will reply and the preprocessor can channel the data to the modem. In the event of a VMCM malfunction, the preprocessor has a timeout function and will turn off the carrier keeping the line quiet.

Supported by: ONR under Contract N00014-84-C-0135, NR 083-400.

WHOI Technical Report 87-55.

## THE COMPILATION OF MOORED CURRENT METER DATA FROM THE NORTH PACIFIC, (THE "ZONAL" EXPERIMENT, 1983-1985) VOLUME XLI

Ellen Levy and Susan A. Tarbell

Summaries of long-term current, temperature and pressure measurements from moored instruments in the western Pacific Ocean (ranging from 152°W to 165°E longitude and 31° to 41°N latitude) are presented. There were two consecutive settings of instru- ments, referred to as Zonal I and Zonal II, each spanning a one-year interval. There were, for the first time, 2 two-year mooring deployments, which were successful. Tables, plots and statistics include filtered and unfiltered data, as well as merged and single setting data. The objective of the experiment was to define the basic properties of the low frequency variability in the mid-latitude North Pacific.

Supported by: ONR under Contracts N00014-76-C-0197, NR 083-400 and N00014-84-C-0134, NR 083-400.

WHOI Technical Report 87-20.

## SATELLITE IMAGE PROCESSING FOR THE AGULHAS RETROFLEXION REGION

Kelly Luetkemeyer

In order to analyze the Advanced Very High Resolution Radiometer satellite data from South Africa, a software package has been written. Methodology and algorithms are described which create geometrically corrected registered satellite images over the Agulhas Retroflexion region. Also discussed are programs to overlay latitude and longitude lines, ship tracks, and ancillary data. A method of masking the land and compositing images for cloud removal is also described.

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WHOI Technical Report 87-27.

## AIR TEMPERATURE SHIELD TESTS

Richard E. Payne

Measurements were made with a group of sensors for 37 days at the end of a dock in Vineyard Sound. The sensors included: a thermistor in an R. M. Young aspirated air temperature radiation shield, a thermistor in an R. M. Young multiplate shield, wind speed and direction, and solar irradiance. For the last eight days we also included a WHOI build cylindrical radiation shield. For wind speeds above 2 m $s^{-1}$, the multiplate shield had an RMS error relative to the aspirated shield of 0.2-0.3 C during daylight hours. Adding a correction linear in solar irradiance decreased the error by a factor of one third to one half. The cylindrical shield appears to have performed better than this but there was insufficient data to support this conclusion statistically.

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WHOI Technical Report 87-40.

## SEQUAL METEROLOGICAL DATA FROM MOORINGS S2, S5 AND S6 (MARCH 1983 - MARCH 1985)

Richard E. Payne

This report presents meteorological data from three deployments of SEQUAL moorings S5 and S6 (nominal positions 0N, 24W and 0N, 15W) and also from a post SEQUAL deployment at SEQUAL mooring site S2 at 0N, 28W. Parameters recorded include vector averaged wind speed and direction, air and sea surface temperatures, insolation, barometric pressure and relative humidity although not all parameters were recorded on all deployments. All deployments were nominally six months.

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WHOI Technical Report 87-30.

## TROPIC HEAT MR METEOROLOGICAL DATA (APRIL 1984 - JUNE 1985)

Richard E. Payne

This report presents meteorological data recorded by the MR on the three deployments of Tropic Heat moorings, within 1.5 degrees north and south of the equator at approximately 134W and 140W. Parameters recorded included vector averaged wind speed and direction, air and sea temperatures, insolation, barometric pressure, and relative humidity although not all parameters were recorded on all deployments. The deployments were all nominally six months. Data recovery was poor because of instrument and mooring failures.

Supported by: NSF under Grant OCE-83 10982.

WHOI Technical Report 87-47.

## SITE L SOFAR FLOAT EXPERIMENT, 1982 - 1985

James F. Price, Theresa K. McKee, W. Brechner Owens and James R. Valdes

Lagrangian measurements of low frequency currents in the vicinity of the Gulf Stream and its recirculation region in the western Sargasso Sea were made by tracking SOFAR floats. These floats were tracked using acoustic time of arrival information from an array of five Autonomous Listening Stations (ALSs) which were moored in the western Sargasso Sea. The ALSs performed almost flawlessly, returning over 90 percent of the possible data.

Floats were released in three deployments of seven floats each in November 1982, February 1983, and June 1983. The floats were launched in initially coherent arrays (approximately 20 km spacing) at 34°N, 70°W, Site "L", and were ballasted for 700 m depth. The SOFAR floats themselves functioned with somewhat less than expected reliability; four floats failed fairly soon after launch, and several other floats suffered failures of their temperature and pressure telemetry.

The majority of the SOFAR floats launched in this program produced long, and interesting trajectories. These new data will be valuable fort estimating first order flow statistics in the dynamically important recirculation region, for visualizing interactions between the Gulf Stream and the New England Seamount Chain, and for estimating one and two particle diffusivities in a region of very high eddy energy.

Supported by: NSF under Grant OCE81-17467.

WHOI Technical Report 87-52.

## TIDE- AND WIND-FORCED CURRENTS IN BUZZARDS BAY, MASSACHUSETTS

Richard P. Signell

Buzzards Bay is an embayment located in southeastern Massachusetts which is roughly 50 km long, 15 km wide, and has an average depth of 11 m. Freshwater input is minimal ($15\ m^3\ s^{-1}$) and currents over most of the bay are dominated by tides. The tidal current is basically rectilinear in the along-bay direction, and the amplitude decreases from a maximum of 50-60 cm $s^{-1}$ near the mouth to 10-15 cm $s^{-1}$ at the head, exhibiting a standing wave response.

Subtidal currents in Buzzards Bay were examined from six current meters on three moorings near the mouth from August 1984 to January 1985. Conditions were vertically well mixed over most this period, and measurements made at 5 and 10 m in roughly 15 m of water show barotropic mean flow dominated by tidal rectification. These Eulerian mean observations are shown to be consistent with the predictions of a non-linear numerical tidal model of the region, which indicates that the lower bay Eulerian mean field is dominated by small scale (2-5 km) tide-induced residual eddies with magnitudes of 1-5 cm $s^{-1}$.

Subtidal current variability is polarized along the axis of the bay, and appears driven by local wind stress. Local wind stress acting along the bay drives a coherent up-wind response at 10 m

depth, but is not coherent at 5 m. In addition, along-bay current energy levels are higher at the central, deepest mooring. A constant depth, steady 1-D model predicts a zero-crossing in current at 1/3 the water depth, providing an explanation for the lack of coherence at the upper instruments. When cross-channel structure is added, the model successfully predicts higher energy levels at the deeper mooring but erroneously predicts a coherent response at the surface instrument.

Transport of material should be due dominantly to the interaction of the local wind response and the tide-induced dispersion indicated by the small scale Eulerian residual field.

Supported by: Department of Commerce, NOAA Office of Sea Grant under Grant R/P-13 and R/P-21; NSF under Grant OCE84-17769; Battelle Memorial Institute; WHOI Coastal Research Center; and WHOI Education Program.

## THE EFFECTS OF DOUBLE-DIFFUSION ON A BAROCLINIC VORTEX

Wendy M. Smith

Laboratory experiments were performed to study the combined effects of double-diffusion and rotation on an oceanic intrusion. Intrusions are driven across density-compensated fronts by the divergence on the double-diffusive buoyancy flux. The increased momentum transport across a double-diffusive interface, however, acts to oppose the action of the buoyancy flux. Turbulent double-diffusive Ekman layers could be a means of redistributing momentum.

A model of an intrusion was made by injecting salt or sugar solution at the surface of a denser layer of sugar or salt solution in a rotating tank to form a baroclinic vortex. The size and shape of the vortex and the velocity structure of the intrusion were measured as functions of time. The double-diffusive vortex spread more quickly and had slower azimuthal velocities than a non-double-diffusive one. This effect increased as the density ratio approached unity. These results indicate that momentum transport across a double-diffusive interface is larger than that across a non-double-diffusive one; thus, the parameterization of friction in an intrusion model should be considered carefully.

Supported by: NSF under Grant OCE84-09323.

WHOI Technical Report 87-26.

## MOORED CURRENT METER DATA FROM THE CANARY BASIN NEAR 32°N, 24°W (1984-1986) VOLUME XL

Susan A Tarbell, Philip L. Richardson and James F. Price

Data are shown from a two-year current meter mooring in the Canary Basin near 24°N, 32°W. Current meters were located at depths of 470 m, 970 m, 1070 m and 2970 m during the period October 19, 1984 to October 4, 1986. The mooring deployment is part of an 1984-1988 experiment to measure features of advection and diffusion of Mediterranean outflow water with neutrally buoyant SOFAR floats.

Supported by: NSF under Grants OCE82-14066 and OCE86-00055.

WHOI Technical Report 87-19.

## TECHNICAL ACTIVITIES ASSOCIATED WITH THE ZONAL PACIFIC ARRAY

George H. Tupper

Geographical exploration of the eddy and mean fields in the world's oceans using moored instrumentation was concentrated in the North Atlantic in the 1970s. Initial efforts to obtain zero-order coverage in the North Pacific were begun with an array across the Kuroshio Extension along 152°E with instruments in the water from mid-1980 to mid-1982. An array designed to extend this exploration zonally with long-term moorings east of 152° at mid-latitudes was first set in the fall of 1983, redeployed in the fall of 1984, and recovered for the final time in late 1985. The array was located along four lines of longitude 165°E, 173°E, 175°W, and 152°W. Along the three westernmost longitudes, 24 one-year moorings were used, 12 each year, with three current meters per mooring at nominal depths of 150, 650, and 4,000 meters. The eastern longitude, 152°E, was sampled by two additional moorings, each with 3 current meters at the above depths, which were deployed for a two-year period, a first for the Buoy Group.

This report addresses the technical activities associated with the 1983-1985 array, referred to hereafter as "ZONAL".

Supported by: ONR Contracts N00014-76-C-0197, NR 083-400 and N00014-84-C-0134, NR 083-400.

WHOI Technical Report 87-54.

# A COMPUTER PROGRAM FOR CALCULATING FREQUENCIES AND MODAL STRUCTURES OF FREE COASTAL-TRAPPED WAVES

John L. Wilkin

A listing and full documentation is presented for a computer program named CTWEIG which computes the frequencies and across-shelf modal structures of free coastal-trapped waves in a costal channel. The three velocity components, mass transport streamfunction, density and pressure perturbation fields are computed. The solution procedure used (horizontal finite differences on a staggered grid and an expansion in the vertical in terms of modified Chebyshev polynomials) makes the solution compatible (without interpolation) with the numerical scheme employed in Haidvogel's (1987) primitive equation ocean circulation model.

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WHOI Technical Report 87-53.

# MARINE POLICY
# AND OCEAN MANAGEMENT PROGRAM
James H. Broadus III, Director

## COASTAL MANAGEMENT IN THE UNITED STATES: A SELECTIVE REVIEW AND SUMMARY

Jack H. Archer

Coastal management in the United States developed in response to two major imperatives: (1) the need to protect and preserve threatened coastal resources and (2) the need to manage the use of coastal resources in a rational manner, resolve use conflicts and balance development and preservation of resources. The structure of the national coastal management program established to meet these needs has been heavily influenced by the federalist character of the U.S. government. Thus, the national program is decentralized and dependent upon state agencies and authorities to achieve national goals and standards set by the Coastal Zone Management Act. Yet the federal government retains sufficient authority to ensure that the four basic goals and nine performance standards of the Act are met by state programs. This report describes state and national program performance in relation to each of the major coastal management goals, and discusses the techniques used to achieve these goals. Special attention is given to monitoring and enforcement activities, environmental assessment in the decision-making process, and the role of public education in coastal management. Selected state programs are reviewed, and a sampling of state coastal management projects through 1985 are listed. This report is primarily intended for foreign readers seeking information about the U.S. coastal management program.

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## THE FLOWER GARDEN BANKS MARINE SANCTUARY: PROTECTING MARINE RESOURCES UNDER INTERNATIONAL LAW

Jack H. Archer

The Flower Garden Banks, in the northwestern Gulf of Mexico and within the boundaries of both the U.S. continental shelf and exclusive economic zone, were first proposed for designation as a national marine sanctuary under the Marine Sanctuaries Act in 1977 in order to protect valuable coral resources from injury caused by vessels dropping and dragging massive anchors on the Banks. The National Oceanic and Atmospheric Administration has had the proposal under review since that time. In 1984, the Department of State agreed that the resources of the Flower Gardens could be protected consistently with international legal principles, but did not specify on what basis the United States could assert jurisdiction to prohibit anchoring by foreign vessels transiting the area - an incident of the high seas freedom of navigation. This paper examines several sources of international law (the 1958 Convention on the Continental Shelf, port state authority, and coastal state authority over the resources of its exclusive economic zone) that sanction such action by a coastal state, and concludes that the United States may prohibit anchoring by foreign vessels in the Flower Garden Banks.

In press: Oceanus, March, 1988.

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## U.S. MANAGEMENT OF MARINE AND COASTAL RESOURCES

Jack H. Archer

This paper focuses on the U.S. experience in managing marine and coastal resources since the late 1960s and early 1970s, a period in which many U.S. marine and coastal programs originated. Three sectors of the U.S. management regime are addressed: fisheries, offshore oil and gas, and offshore minerals; one important and controversial use of the oceans - as a "sink" for dumping and incinerating waste materials - is also mentioned. The management regimes for fisheries and offshore oil and gas are well developed in the United States. The regime for offshore minerals exists in rudimentary form, given the somewhat distant prospects for offshore minerals development. The dumping of toxic materials is prohibited by U.S. law, while at-sea incineration remains controversial and unavailable in the United States as a means of disposing of large quantities of liquid wastes. The paper discusses the major characteristics of the U.S. ocean and coastal resource management regime - its sectoral nature and the relatively high occurrence of use conflicts and jurisdictional disputes among levels of government.

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## IMPLEMENTATION OF THE FEDERAL CONSISTENCY DOCTRINE: LAWFUL AND CONSTITUTIONAL

Jack H. Archer and Joan Bondareff

This paper argues that state implementation of the federal consistency doctrine has been both lawful and constitutional. The authors examine the policy of coastal resource management established by the Congress in the Coastal Zone Management Act, review national and state implementation of the federal consistency doctrine, which requires federal agencies and persons seeking federal permits to conduct their activities and projects affecting coastal resources consistently with state policies, analyze recent federal and state court rulings applying the doctrine, and consider the effects of the doctrine upon federal-state relations. This article is part of a debate sponsored by the editors of the Harvard Environmental Law Review on state actions under the consistency provisions of the Coastal Zone Management Act.

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WHOI Contribution No. 6634.

## EMERGING POLAR SHIP TECHNOLOGY: AN INTRODUCTION

Lawson W. Brigham

The application of modern marine technology to polar ship design and operation has been particularly impressive during the past three decades. Several nations have designed and built remarkedly capable ships for Arctic and Antarctic operations. Extraordinary polar voyages, most thought to be impossible to achieve by surface ship, have included two transits by Soviet nuclear icebreakers to the Geographic North Pole, winter transits by polar icebreakers into the Chukchi and Beaufort Seas, winter oceanographic work aboard a polar research icebreaker in the Weddell Sea, and independent icebreaking cargo ship transits across the Northern Sea Route and in the Canadian Arctic. This successful application of a broad range of new technology to polar ship design and navigation has allowed access by these ships to remote polar regions that were once deemed impenetrable.

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## FINLAND BREAKS THE ICE

Lawson W. Brigham

Finland is the only nation in which the entire coastline and all ports are icebound in winter. The Finnish National Board of Navigation officially classifies 22 of the ports as "winter ports," and declares them open to ice-strengthened merchant vessels. To maintain the winter ports' accessibility, Finland has invested heavily in a modern Baltic icebreaker fleet, operated by the Board of Navigation under the Ministry of Trade and Industry. These ships directly support Finland's economic well-being by enabling the nation to conduct international trade during the winter; they also give the Finnish shipbuilding and steel industries a vehicle for testing new concepts in icebreaker technology.

The importance of Finland's Baltic icebreaker fleet should not be underestimated. For a small nation intimately linked to the sea during winter, these specialized icebreakers represent an enormous capital investment. They keep Finland's foreign trade alive in the winter months. They give Finnish shipbuilding and heavy industries a testing ground for innovative technology. These technical advances, in turn, clearly influence the design of other polar icebreakers and icebreaking cargo vessels, particularly those Finnish shipbuilders provide to the Soviet Union. For the Finnish state, the icebreaker fleet is a significant maritime presence in the Baltic, and a key element in the maritime trade policies so vital to a country of limited resources.

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## MARINE ACCESS IN THE ARCTIC OCEAN: SOVIET, CANADIAN AND AMERICAN APPROACHES

Lawson W. Brigham

The growing importance of the Arctic underscores the need for Arctic rim nations to maintain a credible maritime presence in the region. Although submarines are

significant strategic and military assets, most non-military interests of the Arctic states require support from above the ice cover. Resource development, polar logistics, scientific research, emergency response, surveillance and, potentially, protection of one's sovereignty, can be conducted effectively from icebreaking or ice-capable ships. Surface vessels are important assets since they represent a sustainable capability in Arctic waters and because they inherently provide a visible and viable presence for a coastal state. The strategic and geopolitical advantages of ship access throughout the hostile environment of the Arctic Basin should not be underestimated.

In press: Proceedings, The Polar Regions Seminar, Center for Oceans Law and Policy, University of Virginia School of Law.

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## NEW SOVIET ANTARCTIC RESEARCH SHIP AKADEMIK FEDOROV

Lawson W. Brigham

The Finnish shipbuilder Rauma-Repola OY is currently completing a new Antarctic research ship for the Soviet Union. The 140-meter AKADEMIK FEDOROV will be an Antarctic expedition vessel capable of resupplying Soviet stations and transporting 160 personnel to their research bases. Besides functioning as a multi-purpose passenger and cargo vessel, this icebreaking ship will be a floating research station equipped with ten laboratories designed for a wide spectrum of atmospheric, marine and polar sciences. A 20,000 horse-power diesel-electric plant should provide all power needs and allow continuous icebreaking through 1-meter thick ice. The AKADEMIK FEDOROV will also be fitted with the most modern polar navigation equipment, research computers, and bow and stern thrusters for positioning. The new flagship will provide the Soviet Union with an enhanced maritime presence around the Southern Continent and is indicative of an active, influential involvement in Antarctic marine sciences.

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## THE SOVIET MARITIME ARCTIC PROCEEDINGS OF A WORKSHOP

Lawson W. Brigham

This report is a summary of an international workshop on the Soviet Maritime Arctic held May 10-13, 1987 by the Marine Policy Center of the Woods Hole Oceanographic Institution. Twenty-eight scholars from Canada, Great Britain, Norway and the United States participated. The workshop provided a forum for Western scholars to examine and discuss Soviet domestic and international policies regarding the Arctic Ocean. Interdisciplinary workshop sessions addressed the following concerns: strategic, geographic, historical, legal, scientific, technological, transportation, geopolitical and resource development. This report includes an overview of the workshop, 15 abstracts of contributed papers (8 with figures or tables), and an edited transcript of the concluding discussion session. Appendices include the final program, a list of participants and a list of discussion questions contributed by the participants prior to the workshop. Several key findings of the workshop include: more than 500 years of Russian involvement in the Arctic Ocean; USSR operation of the world's largest polar fleet primarily for transportation and resource development; Russian nationalism as a possible driving force in Soviet activity in the Arctic; Soviet concerns for the Arctic representing an amalgamation of interests (economic, security, environmental, resource, others), none of which alone is predominant; probable Soviet participation in international Arctic regimes based on past actions; and, Soviet legislative enactments which indicate that the balance of interests embodied in the Law of the Sea Convention are largely acceptable to the Soviet Union and that extreme doctrinal views on the legal status of polar seas do not enjoy support in law or State practice. (Russian abstract provided.)

In press: WHOI Technical Report.

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## TECHNICAL DEVELOPMENTS AND THE FUTURE OF THE SOVIET ARCTIC MARINE TRANSPORTATION SYSTEM

Lawson W. Brigham

The Soviet Union operates the world's largest fleet of polar ships, the majority of which are used along the Northern Sea Route. Technological advancement, adaptation and technology transfer from the West

have played leading roles in the development of this diverse fleet. Since the 1950s the Soviet Union has pioneered the use of nulcear power for Arctic ships. Concurrently, the Finnish shipbuilder Wartsila has provided the bulk of the Soviet conventionally-powered icebreaker fleet. Recent developments include the completion in the USSR of a nuclear, Arctic LASH (lighter-aboard-ship) ship; the building in Helsinki of two shallow-draft, nuclear icebreakers of the TAYMYR class; continued improvement of the successful SA-15 icebreaking cargo ships; and, construction of offshore jackup rigs in the West for exploration in the Barents Sea. The Soviet Arctic fleet of the 1990s will contain a significant component of nuclear-powered ships of extraordinary range and icebreaking capability.

While the Soviet icebreaker fleet's primary role is to support marine transportation, the multi-mission nature of these assets should not be underestimated. These ships have conducted search and rescue, performed logistics to a host of installations, supported scientific operations and served as platforms for engineering research. The fleet provides the Soviet Union with an appropriate capability to project a visible presence anywhere in the Arctic Ocean. The fleet will also serve many roles in direct support of future Arctic offshore development and can support military operations should the need arise.

Ice conditions along the Northern Sea Route continue to be the key determinants for establishing the level of capability of the Arctic fleet. The current fleet, particularly the nuclear icebreakers, are capable of maintaining year-round navigation in the Barents and Kara Seas to the port of Dudinka. Because of the exceptional capability of the SA-15 ships and the nuclear LASH ship SEVMORPUT, the Soviet Union may attain year-round navigation in this region with icebreaking ships operating independently (with minimal icebreaker support). However, icebreaker escort of ships in the Laptev and East Siberian Seas will continue due to the extent of fast ice and the duration of the ice season. Satellite images of these seas reveal broad areas of fast ice and the inflow of pack ice into the region. In the Laptev Sea ice breakup occurs off the Lena and Yana River deltas providing no more than a 6 to 7 month navigation season with substantial icebreaker support. Year-round navigation (in any regular fashion) across the entire Soviet Maritime Arctic would appear to be difficult to attain despite the extraordinary effort and investment.

In press: The Soviet Maritime Arctic: Proceedings of a Workshop, WHOI Technical Report.

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## THE GALAPAGOS MARINE RESOURCES RESERVE AND TOURISM DEVELOPMENT

James M. Broadus

One of the newest and largest additions to the world's growing treasury of marine reserves, the 70,000-square-kilometer Galapagos Marine Resources Reserve, may also be the most fascinating. It is fascinating not only because of the spectacular nature of the Galapagos marine environment but also because of the management issues at stake and the process through which they are being addressed. Declaration of the new Reserve grew out of a master planning effort for the entire archipelago, and the difficult task of devising a practical management plan for the Reserve provides an opportunity to improve the integration and effectiveness of tourism regulation and development efforts with fundamental conservation principles. Details of the Reserve's implementation must still be devised, but the policy and direction are now clear. For the Galapagos marine area, the burden of proof has now been shifted in favor of comprehensive management and protection.

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## GALAPAGOS TOURISM: THE IMPORTANCE OF INDUSTRY STRUCTURE

James M. Broadus

One rationale for a marine reserve is to offer alternative tourist attractions and spread visitor traffic. More generally, elaboration of a marine reserve may be seen as a way to attract more tourists and increase the flow of foreign earnings into Ecuador.

Examination of certain basic economic principles makes it clear that in this context, development of an open-entry, competitive tourism industry, as is happening in Galapagos, may actually lead to reduced economic returns for Ecuador, a transfer of economic surplus from Ecuador to foreign

tourists, and increase in environmental degradation, and eventually to a possible reduction in tourism demand.

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## MARINE MINERALS: MISCONCEPTIONS AND MYTHOLOGIES

James M. Broadus

The name "Galapagos" has been associated with marine polymetallic sulfide (MPS) deposits that form around undersea hydrothermal vents, found hundreds of miles east of the new Galapagos Marine Resources Reserve (at about 0°45'N and 85°5'-86°W at 2500-2900 m depth). These "Galapagos" deposits may have influenced some policy makers during the process of establishing the Reserve.

Marine mineral deposits, such as the MPS deposits ought not to be a consideration in planning and implementing the new Galapagos Marine Resources Reserve. No such deposits have been found within the Reserve, and those found elsewhere are not properly considered resources. Their near-term (1-15 years) prospects are nonexistent and their longer-term (15-75 years) prospects are little better, speculative at best.

In press: Scientific Research and the Galapagos Marine Resources Reserve, WHOI Technical Report.

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## OPTION PRICES FOR GROUNDWATER PROTECTION

Steven F. Edwards

This paper reports results from a contingent valuation study of households' willingness-to-pay to prevent uncertain, future nitrate contamination of a potable supply of groundwater. The functional form of the corresponding logic model is derived from utility maximization theory. Probability of future demand, change in the probability of future supply, and an attitudinal score for interests in the well-being of future generations are significant, positive determinants of option prices. Several implications of these results for aquifer management policy are highlighted.

In press: Journal of Environmental Economics and Mangement.

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## FEDERALISM AND FEDERAL CONSISTENCY

Timothy K. Eichenberg

Since 1972, an effective federal-state partnership has been operating to manage our nation's coastal resources under the Coastal Zone Management Act (CZMA). But the federal agency charged with implementing the CZMA, the National Oceanic and Atmospheric Administration (NOAA), once its strongest proponent, has recently adopted policies that undermine the partnership. This paper reviews these policies, such as NOAA's position on litigation limiting state authority, appeals of state objectives to the Secretary of Commerce under the federal consistency provisions of the CZMA, and efforts to implement state Coastal Zone Management Programs. This new approach is compared with the objectives and purposes of the CZMA and the administration's general views on federalism.

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## SUPREME COURT RULES AGAINST PUBLIC BEACH ACCESS

Timothy K. Eichenberg

Summer is the time the public heads for the beach; it also is the time that the decisions of the United States Supreme Court are released from cases argued during the winter and spring. Next summer it may be a little harder for the public to get to the beach thanks to two recent decisions issued by the Court.

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## WHALERS, WHALES, AND TORTOISES

Bruce C. Epler

For most of us, mention of the Galapagos brings to mind images of tortoises, volcanoes, marine iguanas, or blue-footed boobies. But, it was the resources hidden beneath the seas surrounding the archipelago, namely whales, that brought visitors by the thousands between 1790 and the early 1900s. They came in search of sperm whales, and sometimes seals. What is less well-known is that they left the islands with large numbers of tortoises stored in their holds. The impact of their activities lingers on.

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## THE NATIONAL MARINE SANCTUARY PROGRAM: POLICY, EDUCATION AND RESEARCH

Nancy Foster and Jack H. Archer

This article examines the marine resource management and protection policy set by the Congress in the Marine Sanctuaries Act of 1972, the implementation of the national program established under the Act, and two of its major components - public education in the principles and problems of marine resource protection, and marine science research. Special attention is paid to the 1984 amendments to the Act, which substantially modified the site selection and designation procedures, the early use conflicts which hampered program implementation, the redirection of the program toward active marine resource management rather than merely policing sanctuaries, and program performance to date, which has resulted in the creation of seven marine sanctuaries. Program prospects are also briefly discussed, in view of the need to reauthorize the Sanctuary Program in 1988.

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## CHANGING CLIMATE AND CARIBBEAN COASTLINES

Frank Gable

Tourism is a major source of income in the Caribbean. This fact, coupled with a rapidly increasing population and its accompanying demand for space and resources, means that any rise in relative sea level will have severe repercussions. Such a rise has been documented, and it appears likely that it will continue for the foreseeable future.

The Caribbean is particularly vulnerable to a projected increase in sea level because it is made up largely of island nations that have far more coastal zone per unit of land area than do continental nations. Furthermore, many government and international funding agencies have made, and continue to make, important economic and environmental decisions without considering the possibility of a rising sea level.

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## SCIENCE IN COASTAL AND MARINE AREA MANAGEMENT

Arthur G. Gaines, Jr.

The Galapagos Marine Resources Reserve area encompasses an ocean island complex described within a surprising diversity of scientific disciplines as "unique", "extraordinary", "remarkable". The task of designing a management infrastructure that permits conscious and informed choices among use alternatives, while avoiding unexpected side effects is a challenge deserving of the maximum national and international support possible.

We believe science should play two essential and separate parts in the formulation of the management process: (a) science provides the means for describing the natural features and processes of the archipelago such that management can mesh with the realities of the natural system; and, (b) the needs of the international scientific community for conducting future research (and providing ongoing refinements in "(a)" must be accommodated in structuring the management system. If science is incorporated in both these ways, we feel sustainable products of the Marine Reserve can be: low impact tourism and other island-based economies; international cooperation and goodwill for Ecuador; and

natural history education to enrich the lives not only of Ecuadorians but of all humanity into the distant future.

In press: Scientific Research and the Galapagos Marine Resources Reserve, WHOI Technical Report.

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## GALAPAGOS BIBLIOGRAPHY OF SCIENTIFIC LITERATURE

Arthur G. Gaines, Jr. and Bruce C. Epler

A large number of scientific publications discuss studies conducted in the Galapagos Islands. According to the Charles Darwin Research Station about 20,000 references exist, of which many are cited in an unpublished bibliography produced by the Smithsonian Institution, complete through 1978.

Six computer-based bibliographic sources were searched for references on "Galapagos" for the years 1978-1986. The resulting annotated bibliography is characterized and discussed.

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## SCIENTIFIC RESEARCH AND THE GALAPAGOS MARINE RESOURCES RESERVE

Arthur G. Gaines, Jr. and Hernan Moreano

In 1986 the Government of Ecuador established the Galapagos Marine Resources Reserve encompassing the entire Galapagos Archipelago, an area embracing 55,000 square kilometers of the Pacific Ocean and the underlying seabed. A workshop was held to address the role of scientific information in planning for the management of this new Reserve.

Ten North American scholars and about 30 scholars from Ecuadorian governmental and non-governmental scientific organizations met to discuss the status of scientific information on marine areas surrounding these islands. The workshop also focused on the role this information should play in crafting a management plan that will, (a) recognize and mesh with environmental realities of this complex oceanic setting, (b) incorporate new scientific information as it becomes available, and, (c) accommodate the needs of scientists working in the remote, typically harsh and often unique setting the Archipelago provides the international academic community.

Despite important gaps, considerable scientific information is available to Reserve managers, and examples of the use of scientific information in other marine reserves are available. Important areas of innovation are needed to gather and use science effectively for management of this vast ocean area; remote sensing technology and international cooperation offer promise in this regard.

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## THE CONSERVATION AND DISPOSAL OF OCEAN HARD MINERALS: A COMPARISON OF OCEAN MINING CODES IN THE UNITED STATES

Porter Hoagland III

We compare and contrast existing and proposed ocean mining codes in the United States in the context of contemporaneous efforts to establish disparate systems to dispose of ocean hard minerals. Public mineral disposal is defined here as a form of conservation. Broad public policy goals and specific "core" provisions relating to access, revenue generation, performance requirements, and information management are considered as they influence public ocean mineral disposal. To aid in understanding the relationship between disposal and economic conservation, we separate uncertainty into legal and geologic components, distinguish managerial discretion from management flexibility, identify the potential for preferential treatment of ocean hard mineral development, and describe the advantages of a uniform method for public mineral disposal. For ocean hard minerals, attempts to achieve specified policy goals through their disposal may supplant a goal of economic conservation.

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## PERFORMANCE REQUIREMENTS IN OCEAN MINERAL DEVELOPMENT

Porter Hoagland III

We outline the potential effects of the institution of performance requirements in the management of public minerals. If ocean resource management objectives are to encourage research and development, industrial enterprise, national marine operational expertise, the diversification of supply sources for "strategic" minerals, or other public goals, then it may be important to provide inducements for the diversion of capital and labor resources into ocean mineral development. These measures could be supported with stringent performance requirements so that the policy goals are more likely to be achieved. It should be recognized, however, that such policies could impose costs that will be borne eventually by the public. We survey the limited experience in the use of performance requirements for marine hard minerals in the United States. In the near future, performance requirements may become important factors that influence exploration activity in the case of deep seabed mining.

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WHOI Contribution No. 6399.

## SEABED MATERIAL COMMODITY AND RESOURCE SUMMARIES

Porter Hoagland III and James M. Broadus

Over the past five years, research on marine minerals conducted by the Marine Policy Center at the Woods Hole Oceanographic Institution has attempted to gain a better understanding of the process by which these minerals are brought into productive use in society. This technical report results from concentrated research conducted by a research team under the primary sponsorship of the National Sea Grant College Program. This report provides background documentation for the recent publication: J.M. Broadus, 1987, "Seabed Materials," Science 235(4791): 853-860. It is organized to lead the user directly to sources that may provide further information on particular seabed materials. Several presentations of data in the report are of use in understanding the fundamentals of marine mineral markets including: descriptions of the size of the marine mineral resource base and the size of the markets for onshore and offshore sources of marine minerals; price series for minerals with prospective seabed sources; composite prices for four marine mineral types; consumption and price "elasticities" of mineral reserves; trends in mineral exploration inputs and U.S. federal government expenditures for marine nonfuel resources; maps of existing, proposed, or past entitlements for marine hard minerals; a list of known marine polymetallic sulfide (MPS) deposits and reported grades; world trade flows in zinc and copper; the value of apparent consumption in the United States in relation to imports and recycling; and a bibliography.

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WHOI Technical Report 87-43.

## THE ANTARCTIC MINERALS NEGOTIATING PROCESS

Christopher C. Joyner

Since 1982, a select group of states has been engaged in a series of multilateral negotiations to fashion a regime governing the exploration and exploitation of minerals in the Antarctic region. Because of the controversy in the United Nations over whether Antarctica constitutes a portion of the "common heritage of mankind," these negotiations have attracted increasing publicity, but their modus operandi has been left largely unexamined. The chief purpose of this paper is to analyze the process by which this group of concerned states has pursued national priorities within the decision-making framework and context of the Antarctic minerals negotiations.

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WHOI Contribution No. 6550.

## ANTARCTIC RESOURCES AND REMOTE SENSING BY SATELLITE: THE INTERPLAY OF TECHNOLOGY, MISSION AND LAW

Christopher C. Joyner

Remote sensing by satellite is playing an increasing role in contemporary life, contributing significantly to activities ranging from weather forecasting and international communications, to charting surface elevations and mapping coastlines, to measuring pollution output and searching for locations of natural resources. Indeed, satellites are capable of observing vast regions in a very short time, although data acquired from remote sensing coverage must be interpreted in terms of the physical characteristics of that segment of the surface sensed. Given the largely unexplored, environmentally harsh, and desolately estranged nature of the Antarctic, the southern circumpolar area would appear to invite serious consideration as a prime target for remote sensing activities, especially insofar as resource detection, location and assessment is concerned.

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WHOI Contribution No. 6537.

## A COMPARISON OF SOVIET ARCTIC AND ANTARCTIC POLICIES

Christopher C. Joyner

The Soviet Union is a polar State with multiple polar interests. These interests apply not only to the Arctic, but also to the Antarctic. This paper examines three issues which lend insight into the Soviet Government's perception of its national interest priorities for the respective poles, the policies formulated to attain those priorities, and the geostrategic importance which has been affixed to them.

First, there is the Soviet Union's legal attitude towards territorial claims and sovereignty considerations. In the Arctic, the Soviets have laid claim to the region using a sector device for delimitation, based on proximity and contiguity. In the Antarctic, the Soviet Union denies the validity of seven other States' claims there using those same legal rationales. It also reserves the legal right to make a future claim to the continent based on historical discovery by "Russian sailors and navigators," and continued, albeit not "effective," occupation by Soviet citizens (i.e., scientists) since 1958.

Second, there is the promotion of scientific activities in each pole. In the Arctic, scientific activities are actively conducted, with a particular view towards enhancing the Soviet Union's national security in the region. The Soviet Union's decision during the Third United Nations Conference on the Law of the Sea to move from supporting a relatively free access regime to that of a more restrictive consent regime for scientific research in the Exclusive Economic Zone was, in part, motivated by security considerations. In the Antarctic, Soviet policy towards oppotunities for scientific research adamantly favors absolute freedom and complete access, both on land and in circumpolar waters. This position is legally supported by Article II in the Antarctic Treaty, the international regulatory system in place since 1961 for managing Antarctic activities. The Soviet Union has played an active and important role in Treaty affairs, and has used scientific research opportunities as a legitimate conduit for securing a notable and continual national presence throughout the continent.

Third, distinctions are evident in Soviet policies for managing and exploiting resources in each polar region. In the Arctic, the economics of natural resource development have become especially important in recent years, a fact highlighted by the superabundant deposits of hard minerals and hydrocarbons known to exist in the region. To facilitate domestic industrialization and development, the Northern Sea Route has become increasingly important as a transportation link between the northwest Soviet Union and port facilities in the Pacific. Consequently, the Soviet Government in recent years has moved to tighten oversight of its national rights through this Northeast Passage, and has imposed rather restrictive controls on foreign shipping transiting this route. Contrariwise, in the Antarctic, the Soviet Union insists that all circumpolar waters are high seas, with access to shipping and fishery opportunities there governed by a high seas regimes; i.e., this ocean space must be kept open to all, so that it may be used freely by all. Regarding minerals on the continent, the Soviet Union supports creation of a special Minerals Regime under the Antarctic Treaty System to regulate future development of Antarctic resources. Such a regime would likely enhance the Soviet role in Antarctic affairs, as well as preserve opportunities for Soviet access to and allocation of exploitation rights in the future.

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## CROSSING THE GREAT DIVIDE: VIEWS OF A POLITICAL SCIENTISTS WANDERING IN THE WORLD OF INTERNATIONAL LAW

Christopher C. Joyner

Two conceptual distinctions characteristically have encumbered discussion and analysis of legal issues in the study of world politics. The first is the distinction between morality and national interest, and the second is that between morality and power. It is principally the clash between these concepts and the approaches taken to study them that widens the gap between political science and international law, and aggravates the intellectual tensions between scholars and practitioners in the two disciplines.

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WHOI Contribution No. 6458.

## THE EVOLVING ANTARCTIC MINERALS REGIME

Christopher C. Joyner

The Antarctic Treaty Consultative Parties (ATCP) are moving towards completing negotiation of an Antarctic minerals regime. As determined from the most recent treaty text, four principal organs will comprise the new minerals regime: (1) the Special Meeting of All States, which will allow Non-Consultative Party members some voice in the regime; (2) the Antarctic Minerals Resources Commission, which will be the executive agency for deciding whether or not to open an area in the Antarctic for mineral development; (3) Regulatory Committees for each area, which will be responsible for overseeing any exploration and exploitation activities; and (4) a Scientific, Technical and Environmental Advisory Committee to draft assessments and make recommendations to the Commission on the environmental prudence of going forward with developmental activities.

The success of the Antarctic Minerals regime will turn on the ability of the ATCPs to accommodate their own national interests and priorities with each other and the rest of the international community. The ultimate index of success, however, will lie with the regime's ability to preserve and protect the Antarctic environment given possible pressures to develop Antarctica's unknown mineral and hydrocarbon resources.

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WHOI Contribution No. 6551.

## THE EXCLUSIVE ECONOMIC ZONE AND ANTARCTICA: THE DILEMMAS OF NON-SOVEREIGN JURISDICTION

Christopher C. Joyner

The exclusive economic zone (EEZ) stands as one of the more innovative legal creations emerging out of the protracted and prolonged Third United Nations Conference on the Law of the Sea. It obtained formal embodiment as a maritime jurisdictional concept of Part V (Articles 55-75) of the multilateral treaty text produced by those negotiations, the United Nations Convention on the Law of the Sea (UNCLOS). The UNCLOS, however, fails specifically to address the multifaceted legal and political problems associated with applying maritime jurisdictional zones in general and the EEZ in particular to one unique area of the world--Antarctica. Two distinct theoretical blueprints seem available as future remedies for this deficiency. One option would be to compel the Antarctic situation to fit the jurisdictional mold and criteria set for EEZs under the UNCLOS regime. On the other hand, a second option might attempt to retain the region's exclusivity outside the jurisdictional ambit of the UNCLOS. That is, certain states with special interests in the region take it upon themselves to erect new legal structures which serve the same functions as EEZs, and which are specifically tailored to the special environmental conditions and conservation needs of the region. It is this latter blueprint for action that today appears to be engaging the diplomatic attention of several governments who espouse national historical interests in the Antarctic region, and which is to an appreciable extent, already in progress.

The aims of this paper are threefold. First, the study treats the EEZ as a legal concept embodied in the UNCLOS, with a view to determining the realistic applicability it holds for enhancing maritime jurisdiction offshore Antarctica. Second, the paper seeks to analyze the political milieu in the Antarctic to which the EEZ notion would have to be accommodated. Third, an appraisal is made of the legal milieu in the Antarctic, with particular emphasis on the Antarctic Treaty System and the attendant EEZ-like opportunities it affords.

In press: Proceedings, Convention of the International Studies Association, Washington, D.C.

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WHOI Contribution No. 6457.

## GEOPOLITICAL CONSIDERATIONS AND THE ANTARCTIC TREATY SYSTEM

Christopher C. Joyner

The entire Antarctic Treaty System essentially is predicated upon geopolitical considerations. That is, this international, multi-treaty arrangement is aimed at regulating man's relationship to nature --in particular, the Antarctic--as set expressly within the context of geographical phenomena affecting the dynamics of international politics. This paper, however, focuses on two specific issues of geopolitical importance which hold contemporary salience for the Antarctic Treaty System: (1) the maintenance of international security through non-militarization of the region; and (2) the increasingly prominent role of natural resources in Antarctic affairs, both internally among the Antarctic Treaty Consultative Parties (ATCPs) themselves and externally involving states not members of the Treaty System.

In press: Proceedings, Symposium on The Polar Regions, Center for Oceans Law and Policy, University of Virginia School of Law.

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## NON-MILITARIZATION OF THE ANTARCTIC: THE INTERPLAY OF LAW AND GEOPOLITICS

Christopher C. Joyner

Antarctica is the only continent on which military activities, weapons tests, or troop maneuvers of any sort are formally prohibited. These extraordinary conditions effectively denote a regional zone of non-militarization, which extends northward to encompass all the circumpolar islands, ice formations, and ocean space south of 60° South Latitude. Consequently, not only has the continent of Antarctica--representing ten percent (14.3 million square kilometers) of the earth's land surface--been formally declared by national governments to be an internationally non-militarized zone; so, too, has some 27.3 million square kilometers of circumpolar seas in the Southern Ocean been set aside as a neutralized peace preserve. This condition of non-militarization in the Antarctic has prevailed for nearly three decades and has been sustained and upheld by uniform state practice.

This study aims to achieve three main purposes. First, it seeks to set out traditional geostrategic stakes associated with the Antarctic. The intentions here are (a) to evaluate what geopolitical objectives and military considerations convinced governments that non-militarization of the Antarctic was a desirable policy option; and (b) to assess how denial of military ambitions has served mutual national interests such that the relevant states have thus far remained dissuaded from resorting to military means in the area. As its second purpose, the analysis aims to examine the specific provisions of the Antarctic Treaty contributing to non-militarization in the region. The principal objective here is to ascertain more precisely how non-militarization in the Antarctic has been legally stipulated and operationally maintained. Third, the study strives to determine what political and pragamatic factors have contributed most significantly to making the Antarctic Treaty's non-militarization provisions work so effectively over the past twenty-eight years. The purpose of this treatment is to draw out particular lessons from the Antarctic Treaty's successful experience--lessons which might hold some relevance for international law in general and arms control and disarmament measures in particular. The analysis concludes by indicating certain political and legal challenges which could unsettle the present legal regime that has maintained the non-militarized status in the Antarctic.

In press: Netherlands Journal of International Law.

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WHOI Contribution No. 6650.

## THE REALITY AND RELEVANCE OF INTERNATIONAL LAW

Christopher C. Joyner

Students of international relations have often asked certain fundamental questions about the nature and purpose of international law. Is international law really "law"? Or, is it nothing more than "positive morality"? How can international law work in a modern state system dictated by considerations of national interests and power politics? Is international law more of a restraint on national policy, or is it merely a policy instrument wielded by governments to further their own ad hoc purposes to gain legitimacy? In sum, what is the reality and relevance of international law to contemporary world politics? This essay seeks to address these inquiries and in the process to explore the role of international law in contemporary international affairs.

In press: Charles W. Kegley, Jr. and Eugene R. Witthopf (eds.), The Global Agenda: Issues and Perspectives (2nd edition).

Supported by: The Pew Charitable Trusts and the Marine Policy Center.

WHOI Contribution No. 6476.

## A BROAD-SCALE PROFILE OF THE MARINE ADVANCED TECHNOLOGY INDUSTRY

Hauke L. Kite-Powell

A descriptive definition of marine high technology products and companies is proposed, and results of a mail survey of companies comprising this proposed marine high technology group are reported. A profile of the marine high technology industry emerges from information about company background, assets, sales, research and development activity, growth, and employment, as well as data on industry competition, geographic distribution, and the company social structure of the industry. The data suggest that a fairly distinct subgroup of advanced technology companies does exist within the marine technology industry, and that the companies comprising this subgroup display characteristics typically associated with high technology companies.

In press: WHOI Technical Report.

Supported by: The Marine Policy Center.

## NATIONAL OCEAN POLICY: A WINDOW OF OPPORTUNITY

Robert W. Knecht, Biliana Cicin-Sain and Jack H. Archer

This paper analyzes the evolution of U.S. ocean policy from the early 1960s through the present and suggests directions that ocean policy should take in the 1990s. The authors seek to understand why certain ocean policies have been successfully established in the U.S., and adapt the insights developed recently by John Kingdon (1984) to help explain the policy process. According to Kingdon, policy-making in the U.S. is largely determined by development in the "problem", "political" and "policy" streams. When these three separate streams converge, the opportunity for policy initiatives is greatest. But the periodic confluence of these separate streams may not lead to policy change unless proponents of change have well-developed policy alternatives ready to go. This paper anticipates a window of opportunity for ocean policy changes opening in the 1990s, and describes the goals and characteristics of a workable U.S. ocean governance system.

In press: Ocean Development and International Law, Spring, 1988.

Supported by: The Pew Charitable Trusts and the Marine Policy Center.

## SECURITY ASPECTS OF DANISH AND NORWEGIAN LAW OF THE SEA POLICIES

Finn Laursen

Denmark and Norway are strategically located near two of the major Soviet fleets stationed at Kaliningrad and Murmansk. In order for the Baltic Fleet stationed at Kaliningrad to gain access to the high seas of the North Atlantic Ocean, it must pass through the Belts, the Kattegat, the Skaggerak, and the North Sea or the Straits of Dover. In order for the Northern Fleet stationed at Murmansk to gain access to

the high seas of the North Atlantic Ocean, it must pass through the Svalbard Passage between the North Cape of Norway and the Svalbard archipelago down through the Greenland-Iceland-United Kingdom (GIUK) gap. These strategic locations of Denmark and Norway give rise to several security issues that affect the law of the sea policies of both states.

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WHOI Contribution No. 6042.

## SOUTHERN CONE MARITIME SECURITY AFTER THE 1984 ARGENTINE-CHILEAN TREATY OF PEACE AND FRIENDSHIP

Michael A. Morris

The Southern Cone of South America and the adjacent regions of the South Atlantic and South Pacific Oceans, as well as the opposite regions of the Antarctic, present some difficult legal, political, economic, and military problems. As the tip of the Southern Cone has been conflict prone, the political and military interests of Argentina and Chile have tended to predominate. The 1984 Argentine-Chilean Treaty of Peace and Friendship was a significant achievement in conflict resolution, and could lead to greater economic, political and even military cooperation between the two states. Nonetheless, the general area at the tip of the Southern Cone remains conflict prone as evidenced in part by the conflicts over the Falklands/Malvinas Islands, the Beagle Channel, the Drake Passage, and the Antarctic.

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## A CONCEPTION OF THE INTERNATIONAL POLITICAL PROCESS

M. J. Peterson

International politics involves the raising and settling of issues. Actors seek to settle issues through interactions with one another in which they effect an allocation or reallocation of the material and moral stakes involved in a particular matter. Yet many studies of international relations fail to delineate the political process adequately. Structuralists largely ignore the process because they tend to assume that the possession of power or wealth confers the ability to determine outcomes. The modified structuralism prevalent among students of international regimes allows more room for influences from the political process, but usually rests on implicit rather than explicit conceptions of that process. Analysts taking interactionist or interpretive approaches rely heavily on conceptions of the political process in their efforts to understand how actors handle particular interactions or the ways in which commonly accepted images affect actor choices. Yet even their notions of the political process are often implicit. Even the literature on international regimes provides only a partial exception since it focuses mostly on interactions within regimes. Students of domestic politics and foreign policy are accustomed to thinking in terms of an issue or policy process, but their insights have not received sustained attention among analysts studying international relations at the systemic level. Two attempts to conceptualize the international political process suffer from oversimplification at key points, but together provide a stock of ideas from which a more adequate conception can be built.

In press: International Organization.

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WHOI Contribution No. 6594.

## TWO LEGAL OPINIONS ON THE GALAPAGOS MARINE RESERVE: ECUADORIAN LAW

Efrain Pérez (Camacho)

In Ecuador, in the past century, there was already a consensus on the need of a special status for the Galapagos Islands. On May 13, 1986, the Ecuadorian Government established a reserve for marine resources in the Galapagos. The Decree mandates that a management plan be made, which should address policy, management, development, and control of the marine reserve. The Decree also charged an ad hoc committee to come up with a management plan within a six month period that could well be extended far beyond.

As stated in the Constitution of 1883: We need a different set of laws and regulations for the Galapagos. The new Galapagos

statute must contain rules for the adequate improvement of the living standards of the islanders, delicately balanced with the preservation of the archipelago's environment: We should be seeking a true eco-development.

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## TWO LEGAL OPINIONS ON THE GALAPAGOS MARINE RESERVE: INTERNATIONAL ISSUES

Kilaparti Ramakrishna

On May 13, 1986, the President of the Republic of Ecuador decreed the "archipelagic waters" of the Galapagos Islands along with a surrounding band of waters 15 nautical miles in breadth to be a "Marine Resources Reserve" falling under the "exclusive domain" of Ecuador. The decree recounts several steps taken by Ecuador in the past that accorded highest priority to the protection and preservation of a large number of unique ecological features of the islands.

The 1986 decree, as drafted, raises interesting international legal issues. These are issues that arise when any coastal State proposes to designate a given area as a marine park or sanctuary.

Treating the terrestrial and marine environments as one large marine ecosystem and adopting an ecosystem concept of management in Galapagos is urgently needed. At the same time, the Government of Ecuador should consult with the concerned/competent international organizations in obtaining wider support of the Galapagos as a specially vulnerable area and convincing them that special regulations are warranted to safeguard its environment for future generations.

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## SCUBA DIVING IN THE GALAPAGOS ISLANDS: A STUDY OF DIVING SAFETY WITH RECOMMENDATIONS

Margaret A. Rioux and Terrence M. Rioux

The marine environment surrounding Ecuador's Galapagos Islands consists of diverse ecosystems populated by a rich and varied array of organisms. A growing awareness of the unique attributes and scientific importance of this marine resource has spurred increases in scientific research, prompted the Government of Ecuador to establish a marine reserve within the islands and enabled tourist companies to attract recreational divers. The first section of this report summarizes the development and status of diving within the islands. Special attention is paid to the tourist industry which is responsible for promoting and overseeing most of the diving activities in the islands. The second section presents suggestions to strengthen diver and environmental protection. Specific topics addressed include: a brief description of diving conditions and the recommended levels of diving skill, qualifications and training of naturalist diving guides, a discussion of medical treatment available within the islands, a description of facilities for hyperbaric treatment of diving injuries along with their locations and evacuation procedures.

Supported by: The Tinker Foundation and the Marine Policy Center.

WHOI Technical Report 87-22.

## A BAYESIAN APPROACH TO STATISTICAL INFERENCE ABOUT CLIMATE CHANGE

Andrew R. Solow

A Bayesian approach to statistical inference about climate change based on the two-phase regression model is presented. This approach is useful when non-observational information is available about possible climate change. This information may refer to the timing or the nature of the possible change. The approach is applied to an historic temperature record.

In press: Journal of Climate and Applied Meteorology.

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WHOI Contribution No. 6709.

## DETECTING CHANGES THROUGH TIME IN THE VARIANCE OF A LONG-TERM HEMISPHERIC TEMPERATURE RECORD: AN APPLICATION OF ROBUST LOCALLY WEIGHTED REGRESSION

Andrew R. Solow

Historic records of global or hemispheric temperature are an important source of information about climate change. In order to analyze such records statistically, it is necessary to have some knowledge about the behavior of their variances through time. A modified version of robust locally weighted regression, a non-parametric regression procedure, is used to study the behavior of the variance for a record of Southern Hemisphere temperature deviations. Sampling considerations suggest that the variance should decrease through time, as new recording stations are added to the sampling network. Surprisingly, the variance is found to remain virtually constant through time.

In press: Journal of Climate and Applied Meteorology.

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WHOI Contribution No. 6646.

## A COUNTER-INTUITIVE RESULT FOR MIXTURE RANDOM FIELDS

Andrew R. Solow

A random field consisting of two or more non-overlapping components (e.g., soil types) is called a mixture random field. Suppose a two-component mixture consists of a spatially correlated component and a spatially uncorrelated component. This paper shows that the spatial correlation for the overall field can be stronger than the spatial correlation in the correlated component. The result is explained in terms of the difference between two component means and the expected length per unit area of the boundary between the components.

In press: Mathematical Geology.

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WHOI Contribution No. 6706.

## A SIMPLE MODEL OF OVER-FORECASTING

Andrew R. Solow and James M. Broadus

Probabilistic forecasts of the occurrence of precipitation have been used routinely in the United States since 1965. Studies of the reliability of such forecasts often show a tendency towards over-forecasting (i.e., for forecast probabilities to exceed observed relative frequencies). A simple model is described that explains over-forecasting in terms of an asymmetric loss function. The model is applied to some results of a previous study.

In press: Monthly Weather Review.

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WHOI Contribution No. 6652.

# GRADUATE STUDENTS

Abstracts of papers or theses submitted in 1987 by graduate students of the Woods Hole Oceanographic Institution Doctoral Degree Program and the Woods Hole Oceanographic Institution/Massachusetts Institute of Technology Joint Program in Oceanography/Oceanographic Engineering. Other papers authored or coauthored by graduate students are included in the departmental sections. Students are indicated by an asterisk in the Author Index.

## INTERPRETATION OF EQUATORIAL CURRENT METER DATA AS INTERNAL WAVES

Martin Benno Blumenthal

Garrett and Munk use linear dynamics to synthesize frequency-wavenumber energy spectra for internal waves (GM72, GM75, GM79). The GM internal wave models are horizontally isotropic, vertically symmetric, purely propagating, and universal in both time and space. This set of properties effectively eliminates all the interesting physics, since such models do not allow localized sources and sinks of energy. Thus an important step in understanding internal wave dynamics is to make measurements of deviations from the simple GM models.

This thesis continues the search for deviations from the GM models. It has three advantages over earlier work: extensive data from an equatorial region, long time series (2 years), and relatively sophisticated linear internal wave models. Since the GM models are based on mid-latitude data, having data from an equatorial region which has a strong mean current system offers an opportunity to examine a region with a distinctly different basic state. The longer time series mean there is a larger statistical ensemble of realizations, making it possible to detect smaller internal wave signals. The internal wave models include several important extensions to the GM models: horizontal anisotropy and vertical asymmetry, resolution between standing modes and propagating waves, general vertical structure, and kinematic effects of mean shear flow. Also investigated are the effects of scattering on internal waves, effects that are especially strong on the equator because the buoyancy frequency variability is a factor of ten higher than at mid-latitudes.

In the high frequency internal wave field considered (frequencies between .125 cph and .458 cph), several features are found that are not included in the GM models. Both the kinematic effects of a mean shear flow and the phase-locking that distinguishes standing modes from propagating waves are observed. There is a seasonal dependence in energy level of roughly 10% of the mean level. At times the wave field is zonally and vertically asymmetric, with resulting energy fluxes that are a small (4% to 10%) fraction of the maximum energy flux the internal wave field could support. The fluxes are, however, as big as many of the postulated sources of energy for the internal wave field.

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## TOMOGRAPHIC MEASUREMENTS OF BAROTROPIC MOTIONS

Paul J. Bushong

In 1983, continuous acoustic transmissions centered at 133 Hz and with a resolution of 60 ms were transmitted for five days from Oahu to the coast of Northern California (4000 km range). A maximum likelihood estimate of the change in acoustic travel time (based on phase) between received pulses is used to estimate barotropic fluctuations. Analysis of the resulting time series reveals resonant oscillations at nontidal frequencies in the Northeast Pacific. Some of the periods of the resonant oscillations are consistent with theory (Platzman, Curtis, Hansen, and Slater, 1981).

A Wiener filter is formulated for estimating the barotropic tides from a basin scale tomographic array. Error analyses indicate an ability to estimate barotropic currents and surface displacements with errors less than 0.01 cm/s and 1 cm, respectively, over a large portion of the Northeast Pacific.

Supported by: the United States Navy.

## DESIGN AND PERFORMANCE ANALYSIS OF A DIGITAL ACOUSTIC TELEMETRY SYSTEM

Josko A. Catipovic

This work studies the application of current communication engineering methods to underwater acoustic telemetry. The underwater channel is modelled with data collected from channel probe experiments in Woods Hole Harbor and the Marginal Ice Zone. The experimental results indicate that the short range underwater acoustic channel may be modelled as a time dispersive fully saturated channel. In all cases the received signal phase is fully random for time intervals longer than 10 msec, and the envelope is characterized by a fully fading Nakagami PDF.

It is shown that PSK modulation methods are ineffective because of the rapid phase fluctuations of received transmissions, and that the performance of the optimal partially coherent FSK receiver is almost identical to the suboptimal incoherent FSK demodulator. Adaptive equalization and impulse response measurement techniques for the underwater acoustic channels are presented.

Data coding for the ocean acoustic channel is interpreted as a tradeoff between increased diversity level and resultant data reconstruction ability on one side and the increased incoherent

coding loss and system complexity on the other. The time-variant nature of the channel is coupled to a time-variant decoding algorithm capable of isolating regions of poor data quality and modifying the performance vs. complexity curve to decode the data stream within a hardware and real-time constraint.

Performance of convolutional codes and sequential decoders on the Rayleigh fading channel is discussed, and complexity bounds for sequential decoding on the memoryless fading channel are discussed as a function of optimal and/or available system diversity. It is shown that sequential decoding of convolutional codes is a viable technique given the contemplated data rates and currently available decoding hardware.

Frame synchronization on the Rayleigh fading channel using a modification of sequential decoding algorithms is discussed. The Maximum Likelihood (ML) synchronizer for the fading channel is derived and presented as an implementation of the ML sequence estimator implementable with the Viterbi or sequential decoding algorithm.

A digital simulation of data modulation, coding and equalization on a realistic model of the underwater channel is carried out and described. Sequential coding of convolutional codes is shown to be a viable and implementable technique for the underwater channel.

A discussion of decoder complexity and physical size in the light of available digital hardware is presented. This section is not intended as a detailed design guide, but gives a clear indication that the proposed and discussed communication system can be efficiently realized and is compact enough to be useful to the users of the underwater channel.

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## ON THE ROLE OF TOPOGRAPHY AND OF BOUNDARY FORCING IN THE OCEAN CIRCULATION

Paola Cessi

This thesis consists of two loosely related problems, both of which analyze some consequences of the failure of Sverdrup relation. In the first part, Chapters 2 and 3, the Sverdrup relation is invalidated because substantial flow is obtained at the bottom where topography exists. The eddies play an essential role in transferring momentum vertically from the surface, where the forcing is applied, to the bottom, which is otherwise unforced. If the topography has a structure in the longitudinal direction, then the inviscid theory predicts the occurrence of strong jets in the interior of the model ocean. According to the structure of the topography these internal jets can occur in both vertically homeogenous and baroclinic oceans. If the topographic slope changes sign, then one kind of jets is observed both in stratified and in homogeneous oceans. This phenomenon is robust to moderate amounts of dissipation and is not disturbed by the occurrence of recirculating gyres within the basin.

If the topographic slope is constant, then another kind of internal jets is observed, and it occurs in stratified models only. I was unable to observe this kind of jets in the presence of weak dissipation. The reason for this failure is twofold: on one hand friction, especially interfacial friction, tends to make the flow more barotropic (and we believe that indeed this is one of the processes that the eddies accomplish in a stratified fluid) and therefore the phenomena that rely strongly on baroclinicity are discouraged. On the other hand, reduction of the dissipation leads to the onset of a strong recirculating, inertial gyre which, although confined in space, affects the global properties of the flow.

In the second part of the thesis (Chapters 4 and 5) I developed a simple model of the recirculating, inertial gyre. Again the dynamics of this feature are far from being in Sverdrup balance. In this case inertia is responsible for the failure of Sverdrup relation, together with the eddy field which provides a mean for transferring momentum vertically and laterally into regions away from where the forcing is applied. In this model there is no direct forcing in the recirculation region, and the input of momentum is confined to the boundary currents surrounding the gyre, for example the separated Gulf Stream.

One of the results of the recirculation model is the prediction of its transport. It is shown that most of the transport is depth independent, i.e. it can be calculated without detailed knowledge of the density structure of the ocean. It is also shown that the "barotropic" part of the transport increases as the cube of the meridional extent of the gyre.

Supported by: NSF Grant ATM 84-13515.

## A PRONY ALGORITHM FOR SHALLOW WATER WAVEGUIDE ANALYSIS

Ferdinand Joseph Diemer

Low frequency acoustic propagation in shallow water is examined from a normal mode context. By modelling the far field pressure field as a modal sum, propagating mode characteristics of wavenumber, initial phase, attenuation and amplitude may be estimated using a high resolution parameter modeling technique. The advantages of such an algorithm are the resolution of closely spaced modes in a range independent environment and the ability to analyze range dependent waveguides.

This thesis presents the application of a Prony algorithm to the shallow water environment. The algorithm operates directly on the signal matrix. Synthetically generated, range independent pressure fields are used to analyze the technique's performance and to observe its sensitivity to variations in model specifications. Noise is added to determine the threshold of acceptable performance. As a consequence of field data tests, further enhancements to the algorithm are suggested.

Range dependent performance is evaluated on a coastal wedge example and geoacoustic parameter shift example.

Supported by: the United States Navy.

## APPLICATION OF SEASAT ALTIMETRY TO TECTONIC STUDIES OF FRACTURE ZONES IN THE SOUTHERN OCEANS

Mavis Lynn Driscoll

Gravity derived from Seasat altimetry has provided a means of estimating seafloor topography and its compensation, which in turn can be used to understand the evolution of oceanic lithosphere. In the first study, the correlation between the geoid, deflection of the vertical, and seafloor topography is investigated along a section of the Southwest Indian Ridge. Geoid anomalies computed from a simple thermal model fairly accurately predict the intermediate-wavelength anomalies across the fracture zones. The shorter wavelength anomalies are consistent with those calculated from topography using elastic plate compensation. The combined effect of the thermal offset and seafloor topography produces an anomaly which has a small-amplitude, short-wavelength depression directly over the fracture zone valley. Pronounced lineations in the horizontal geoid gradient do not coincide with the valley but have trends parallel to the fracture zones.

In the second study, fracture zones along the Southwest Indian Ridge are identified using altimeter profiles and bathymetry. Finite poles of rotation are determined from the fracture zone locations and magnetic anomaly lineations for anomalies 6 (20 Ma), 13 (37 Ma), and 20 (45 Ma). The new poles are in general agreement with previously published poles and describe a fairly consistent direction of relative motion between Africa and Antarctica for the past 45 Myr. A present-day pole of rotation calculated from transform fault azimuths determined primarily from their geoid anomalies, agrees with published poles based on bathymetric data.

In the third study, the rate of change of the geoid with age has been estimated as a function of age from geoid offsets across the Eltanin and Udintsev fracture zones and used to constrain thermal models of lithospheric cooling. Observed trends in the geoid slope versus age plots are similar on both branches of the Eltanin and the east limb of the Udintsev fracture zone. The similarity in trends argues against the effects of isolated thermal or bathymetric anomalies and appears instead to reflect a general feature of the geoid-slope versus average age relationship across fracture zones. Although the thermal plate cooling model is successful in predicting both seafloor depths and heat flow values out to ages of at least 80 m.y. B.P., it cannot explain the observed geoid slope values for these two fracture zones. It is not clear at this point whether this is due to inadequacies in the cooling model or to peculiarities in fracture zone evolution.

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## STATISTICAL SIGNAL PROCESSING USING A CLASS OF ITERATIVE ESTIMATION ALGORITHMS

Meir Feder

Many Signal Processing problems may be posed as statistical parameter estimation problems. A desired solution for the statistical problem is obtained by maximizing the Likelihood (ML), the A-Posteriori probability (MAP) or by optimizing other criterion, depending on the apriori knowledge. However, in many practical situations, the original signal processing problem may generate a complicated optimization problem e.g. when the observed signals are noisy and "incomplete".

A framework of iterative procedures for maximizing the likelihood, the EM algorithm, is widely used in statistics. In the EM algorithm, the observations are considered "incomplete" and the algorithm iterates between estimating the sufficient statistics of the "complete data" given

the observations and a current estimate of the parameters (the E step) and maximizing the likelihood of the complete data, using the estimated sufficient statistics (the M step). When this algorithm is applied to signal processing problems it yield, in many cases, an intuitively appealing processing scheme.

In the first part of the thesis we investigate and extend the EM framework. By changing the "complete data" in each step of the algorithm we achieve algorithms with better convergence properties. We suggest EM type algorithms to optimize other (non ML) criteria. We also develop sequential and adaptive version of the EM algorithm.

In the second part of the thesis we discuss some applications of this extended framework of algorithms. We consider,

- Parameter estimation of composite signals, i.e. signals that can be represented as a decomposition of simpler signals. This problem appear in e.g.
  - Multiple source location (or bearing estimation
  - Multipath or multi-echo time delay estimation
- Noise cancelling in multiple microphone environment, for a speech enhancement problem.

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## PREDICTION OF CONTINENTAL SHELF SEDIMENT TRANSPORT USING A THEORETICAL MODEL OF THE WAVE-CURRENT BOUNDARY LAYER

Margaret Redding Goud

This thesis presents an application of the Grant-Madsen-Glenn bottom boundary layer model (Grant and Madsen, 1979; Glenn and Grant 1987) to predictions of sediment transport on the continental shelf. The analysis is a two-stage process. Via numerical experiment, we explore the sensitivity of sediment transport to variations in model parameters and assumptions. A notable result is the enhancement of suspended sediment stratification due to wave boundary layer effects. When sediment stratification is neglected under conditions of large wave bottom velocities (i.e. $40^{cm/sec}$), concentration predictions can be more than an order of magnitude higher than any observed during storm conditions on the continental shelf.

A number of limitations to application emerged from the analysis. Solutions to the stratified model are not uniquely determined under a number of cases of interest, potentially leading to gross inaccuracies in the prediction of sediment load and transport. Load and sediment transport in the outer Ekman Layer, beyond the region of emphasis for the model, can be as large or larger than the near-bottom estimates in some cases; such results suggest directions for improvements in the theoretical model.

In the second step of the analysis, we test the ability of the model to make predictions of net sediment transport that are consistent with observed sediment depositional patterns. Data from the Mid-Atlantic Bight and the Northern California coast are used to define reasonable model input to represent conditions on two different types of shelves. In these examples, the results show how the intensification of wave bottom velocities with decreasing depth can introduce net transport over a region. The patterns of erosion/-deposition are shown to be strongly influenced by sediment stratification and moveable bed roughness. Also predicted by the applications is a rapid winnowing out of fine grain size components when there is even a small variation of bed grain size texture in the along-flow direction.

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## HELIUM AND LEAD ISOTOPE GEOCHEMISTRY OF OCEANIC VOLCANIC ROCKS FROM THE EAST PACIFIC AND SOUTH ATLANTIC

David W. Graham

The isotopic evolution of helium and lead in the Earth is coupled by virtue of their common radioactive parents uranium and thorium. The isotopic signatures in oceanic volcanic rocks provide constraints on the temporal evolution of mantle source regions and volcanic magmas. He and Pb isotopes were measured in glassy basalts from young seamounts in the East Pacific, and in phenocrysts and corresponding whole rocks, respectively, from the island of St. Helena. He isotopes were also measured in glassy mid-ocean ridge basalts from the South Atlantic, previously studied for Pb isotopes by Hanan et al. (1986).

A precise reconstruction of He-Pb isotope relationships in volcanic source regions is complicated by post-eruptive radiogenic ingrowth of $^4He$ in non-zero age basalts, by pre-eruptive radiogenic ingrowth of $^4He$ in magmas with elevated (U+Th)/He, by multi-stage fractionation processes involving (U+Th)/He, U/Pb and Th/Pb and by convective mixing in the Earth's interior. Aspects of each of these problems are addressed.

(U+Th)/He ages are estimated from the isotope disequilibrium of $^3He/^4He$ between

He trapped in vesicles and that dissolved in the glass phase of young alkali basalts at seamount 6 in the East Pacific. $^3He/^4He$ in the glass phase of these alkali basalts is subatmospheric, while in the vesicles it ranges between 1.2-2.5 $R_A$ ($R_A$ = atmospheric ratio). $^3He/^4He$ in vesicles (extracted by crushing in vacuo) allows a correction to be made in the dissolved phase He (by fusion of the remaining powder) for the inherited component in order to compute the radiogenic [He]. The method is applicable to rocks containing phases with different (U+Th)/He, and the results have implications for dating lavas in the age range of $10^3$ to $10^6$ years, and for reconstructing the temporal evolution of young volcanic systems.

Pb, Sr and Nd isotopic variability observed at a small seamount field between 9-14°N near the East Pacific Rise covers ~80% of the variability for Pacific MORB, due to small-scale heterogeneity in the underlying mantle. Theoleiites at these seamounts have He, Pb, Sr and Nd isotope compositions which are indistinguishable from MORB. Associated alkali basalts show more radiogenic He, Pb and Sr signatures. The lower $^3He/^4He$ of He trapped in vesicles of these alkali basalts (1.2-2.6 $R_A$) is associated with low helium concentrations ( $5x10^{-8}$ ccSTP/g). Evolved alkali basalts have lower $^3He/^4He$ (1.2-1.8 $R_A$) than primitive alkali basalts (2.4-2.6 $R_A$), suggesting some degree of magmatic control on inherited $^3He/^4He$ in these alkalic lavas. Collectively, the isotopic results suggest that as the lithosphere ages, material transfer from the MORB source becomes less significant because smaller degrees of melting average the chemical characteristics of heterogeneous mantle volumes less efficiently than near the ridge.

Icelandites erupted at Shimada Seamount, an isolated volcano on 20 m.y. old seafloor, have Pb, Sr and Nd isotopic compositions similar to post-erosional basalts at Samoa. $^3He/^4He$ at Shimada ranges between 3.9-4.8 $R_A$ and helium concentrations are too large for radiogenic contamination of magma to have lowered the $^3He/^4He$ appreciably. These results indicate the presence of an enriched mantle component previously unidentified beneath the East Pacific. Its low $^3He/^4He$ may be due to the melting of domains with high (U+Th)/He which formed during accretion of the oceanic lithosphere. Alternatively, it is an inherent characteristic of the source, which contains material recycled into the mantle at subduction zones.

The mid-ocean ridge between 12-46°S in the South Atlantic displays $^3He/^4He$ lower than typical MORB values. Local anomalies occur at the latitudes of off-axis islands to the east, apparently due to contamination of depleted mantle asthenosphere by hotspot materials (as previously shown for $(La/Sm)_N$ and Pb isotopes; Schilling et al., 1985; Hanan et al., 1986). He-Pb isotopic relationships along the 12-22°S ridge segment suggest that St. Helena has $^3He/^4He$ less than MORB. $^3He/^4He$ in two St. Helena rocks (extracted by in vacuo crushing of olivine and pyroxene) is 5.8 $R_A$ when the extracted $^3He$ contents are greater than $1x10^{-13}$ ccSTP/g, consistent with the He-Pb observations along the St. Helena ridge segment.

$^4He/^3He$ and radiogenic Pb isotope ratios are linearly correlated for the South Atlantic ridge segment between 2-12°S. Linear correlation of $^4He/^3He$ - $^{206}Pb/^{204}Pb$ within an oceanic rock suite reflects the temporal evolution of $^{204}Pb/^3He$ in the source. A linear correlation between volcanic suites derived from isotopically different sources (e.g., oceanic islands) may imply a coherent fractionation of (U+Th) from He and Pb during the evolutionary history of their respective mantle source regions.

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## PARTICLE FLUX IN THE WESTERN BLACK SEA IN THE PRESENT AND OVER THE LAST 5,000 YEARS: TEMPORAL VARIABILITY, SOURCES, TRANSPORT MECHANISMS

Bernward Josef Hay

The particle flux in the present and over the last 5,000 years was investigated in the Black Sea in a comparative study with samples from time-series sediment traps and laminated core sediments. The sediment trap samples were collected in the southwestern Black Sea over 2-1/2 years at sampling intervals of about two weeks. The sediment core samples were derived from the central part of the western Black Sea, deposited throughout the last 5,000 years during which the Black Sea was anoxic. Conclusions from this study shed important light on the temporal and regional variability of the particle flux in the Black Sea, the dominant particle sources, and the particle transport mechanisms.

Dominant particle sources are biogenic matter (coccolithophorids of the species Emiliania huxleyi, diatoms, and silicoflagellates) and terrigenous matter from the Danube and nearby local rivers. The relative importance in the supply of these particles varies annually and can be grouped into three phases: Phase I (June-October) - coccolithophorid production,

Phase II (November-January) - resuspension of coccoliths and terrigenous matter, and Phase III (February-May) - river input of terrigenous matter and production of diatoms and silicoflagellates. Once removed from the surface water, particles settle rapidly at a rate of 115 70 m/day.

Regionally, the particle flux varies considerably. Throughout the last 1,000 years (sediment unit I), the particle flux (paleoflux) is more than 5 times larger in the central part of the western Black Sea than at present in the southwestern Black Sea, mostly because of the 11 times larger supply of coccoliths. The coccoliths were probably largely produced on or adjacent to the Danube shelf in the northwestern Black Sea and subsequently resuspended and transported offshelf by the fall storms. Terrigenous matter in the central part of the western Black Sea is higher by a factor of 3 compared to the southwestern Black Sea. The coccoliths are concentrated in the white laminae ( 93 $CaCO_3$), and if the seasonal dynamics in the particle supply at the sediment trap site is taken as a standard, the white laminae would be deposited between about June and January. The black laminae contain largely terrigenous matter and form during the peak river discharge period between about February and May.

Compared to the last 1,000 years (unit I), the particle flux in the central part of the western Black Sea between 1,000 and 5,000 years B.P. was smaller by a factor of three, because the salinity was still too low during this time period for the coccolithophorid Emiliania huxleyi to exist. The Black Sea was a fresh water environment before more than 5,000 years ago and gradually became brackish; the establishment of Emiliania huxleyi in the Black Sea would reflect a salinity of about 11‰.

The terrigenous matter supply remained about constant over the last 5,000 years. The western Black Sea is dominated by terrigenous input from the Danube as revealed by the illite/montmorillonite ratio. Seasonally, the terrigenous matter from the Danube appears to be traceable in the southwestern Black Sea, as seen by the Ti/Al and illite/montmorillonite ratios in the sediment trap samples.

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## ECOLOGY AND FEEDING BIOLOGY OF THECATE HETEROTROPHIC DINOFLAGELLATES

Dean Martin Jacobson

A group of thecate heterotrophic dinoflagellates (THDs), principally in the diverse and ubiquitous genus Protoperidinium, was investigated both from an ecological and an organismal perspective. When this study was initiated, nothing was known about their feeding mechanisms, rates or food preferences. The population dynamics of these microheterotrophs in a temperate estuary were studied over a 13 month period, along with co-occurring diatoms, ciliates and pigmented (photosynthetic) dinoflagellates. The timing of several peaks in Protoperidinium abundance coincided with those of diatom blooms, suggesting a possible trophic dependance. During such peaks the biovolume or biomass of the THD community exceeded that of both pigmented dinoflagellates and ciliates. Occurrence patterns of individual THD species were closely related to water temperature; this may indicate the involvement of benthic resting cysts in population succession.

Small-scale vertical distributional patterns of THDs were also studied in an embayment with an average depth of 5 m. While two autotrophic dinoflagellate species displayed distinct daily vertical migration patterns, THD species did not; most species maintained a constant 2-5 m depth of maximum abundance, while two others had surface maxima.

Feeding behavior, as observed in 19 THD species (Oblea rotunda, Zygabikodinium lenticulatum and 17 species of Protoperidinium) fits the following pattern: a THD cell attaches a slender filament to a prey item (usually a diatom) while it is engaged in a characteristic, spiralling "dance". Subsequently, a pseudopod or "pallium" (a term defined here) emerges from the flagellar pore and envelops the prey within a minute. Ten to sixty minutes later the pallium is retracted and the prey (now a nearly-empty frustule) is discarded. Most species feed only on diatoms, but O. rotunda, Z. lenticulatum (both diplopsaloid species) and P. pyriforme also preyed upon dinoflagellates.

Ingestion and growth rates were determined in the laboratory where cultures of Protoperidinium hirobis were fed the diatom Leptocylindrus danicus. Feeding cycles were repeated as often as every 1.5 to 2 hours. Maximal ingestion rates of 23 diatoms$\cdot day^{-1}$ supported unexpectedly high specific growth rates of up to 1.1$\cdot day^{-1}$ (1.7 divisions$\cdot day^{-1}$). Half-maximal growth and grazing rates occurred at approximately 1000 diatoms cells$\cdot ml^{-1}$. Peak division frequencies occurred at night, although feeding rate was nearly constant on a diel basis.

The ultrastructure of the feeding apparatus was studied in Protoperidinium spinulosum. The pallium, when deployed, is composed of a complex system of membranous

channels, vesicles, and a few microtubular ribbons radiating from the flagellar pore. Inside this pore, the pallium is continuous with the contents of an elongate microtubular basket that extends towards the nucleus. The apical end of this basket opens adjacent to the nucleus; at this point its contents become continuous with the central cytoplasmic region. This region is distinguished from the relatively dense, peripheral cytoplasm by the presence of either large electron-lucent vesicles (containing, perhaps, digestive enzymes) or numerous small lipid droplets. Examination of a pre-feeding cell has revealed the likely source of the pallium membranes: dense membranous whorls lie within the microtubular basket. A narrow pseudopodal appendage in two non-feeding cells may constitute the tow filament used in prey capture. A complex myonemal system, including osmiophilic ring, striated collars and connecting bands is described. The microtubular basket and osmiophilic ring structures were also found in Protoperidinium hirobis, Protoperidinium punctulatum and Oblea rotunda.

This thesis has done much to further the understanding of a prevalent component of the protozooplankton, the thecate heterotrophic dinoflagellates. This progress, which was due in a large part to the culture success reported herein, includes new insights into the abundance, feeding behavior, food preferences, feeding rates, and ultrastructural basis of feeding in this preeminent group of the thecate heterotrophic dinoflagellates, the genus Protoperidinium.

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## EXACT RECONSTRUCTION OF OCEAN BOTTOM VELOCITY PROFILES FROM MONOCHROMATIC SCATTERING DATA

Andre A. Merab

This thesis presents the theoretical and computational underpinnings of a novel approach to the determination of the acoustic parameters of the ocean bottom using a monochromatic source. The problem is shown to be equivalent to that of the reconstruction of the potential in a Schrodinger equation from the knowledge of the plane-wave reflection coefficient as a function of vertical wavenumber, $r(k_z)$ for all real positive $k_z$. First, the reflection coefficient is shown to decay asymptotically at least as fast as $(1/k_z^2)$ for large $k_z$ and is therefore integrable. The Gelfand-Levitan inversion procedure is extended to include the case of basement velocity higher than the velocity of sound in water. The neglect of bound states is shown to be justified in both clayey silt and silty clay at the 220 Hz frequency of operation.

Three methods for the numerical solution of the integral equation are investigated. The first one is an "Improved Born approximation" wherein the solution is given as a series expansion the first term of which is the Born approximation while the second term represents a substantial and yet easy to implement improvement over Born.

The two other methods are based on a discretization of the Gelfand-Levitan integral equation, and both avoid a matrix inversion: one by employing a recursive procedure, and the other by coupling the Gelfand-Levitan equation with a partial differential equation. Bounds are obtained on errors in the solution due either to discretization or to data inaccuracy. These methods are tested on synthetic data obtained from known geoacoustic models of the ocean bottom. Results are found to be very accurate particularly at the top of the sediment layer with resolution of less than the wavelength of the acoustic source in the water. Several effects are investigated, such as sampling, attenuation, and noise. Also examined is the gradual restriction of the reflection coefficient to a finite range of vertical wavenumbers and the consequent progressive deterioration of the reconstruction.

The analysis shows how to reconstruct velocity profiles in the presence of density variation when the experiment is conducted at two frequencies.

Our results provide a good understanding of the issues involved in conducting a monochromatic deep ocean bottom experiment and constitute a promising technique for processing the experimental data when it becomes available.

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## ESTIMATION OF SEA SURFACE WAVE SPECTRA USING ACOUSTIC TOMOGRAPHY

James Henry Miller

This thesis develops a new technique for estimating quasi-homogeneous and quasi-stationary sea surface wave frequency-direction spectra using acoustic tomography. The analysis of acoustic (mode and ray) phase and travel time perturbations due to a rough sea surface is presented. Two canonical waveguides (ideal shallow water and linear squared index of

refraction) are used as examples for the mode perturbation. The analysis is used to explain high mode coherence measured in the FRAM IV experiment. The forward problem of computing the acoustic phase and travel time perturbation spectra given the surface wave spectrum is solved to first order. An application of the technique to ray phase data taken during the MIZEX '84 experiment is shown. The inverse problems for the homogeneous and quasi-homogeneous frequency-direction spectrum are introduced. The theory is applied to synthetic data which simulate a fetch-dependent sea. The estimates made agree well with the "actual" (synthetic data) spectrum. The effect of noise in the travel time estimates is studied. The sensitivity of the technique to the number of rays used in the inversion is investigated and the resolution and variance of the inverse method are addressed.

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## THERMALLY DRIVEN CIRCULATION

Haim Nelken

Several problems connected by the theme of thermal forcing are addressed herein. The main topic is the stratification and flow field resulting from imposing a specified heat flux on a fluid that is otherwise confined to a rigid insulating basin. In addition to the traditional eddy viscosity and diffusivity, turbulent processes are also included by a convective overturning adjustment at locations where the local density field is unstable.

Two classes of problems are treated. The first is the large scale meridional pattern of a fluid in an annulus. The detailed treatment is carried out in two steps. In the beginning (chapter 2) it is assumed that the fluid is very diffusive, hence, to first approximation no flow field is present. It is found that the convective overturning adjustment changes the character of the stratification in all the regions that are cooled from the top, resulting in a temperature field that is nearly depth independent in the northernmost latitudes. The response to a seasonal cycle in the forcing, and the differences between averaging the results from the end of each season compared to driving the fluid by a mean forcing are analyzed. In particular, the resulting sea surface temperature is warmer in the former procedure. This observation is important in models where the heat flux is sensitive to the gradient of air to sea surface temperatures.

The analysis of the problem continues in chapter 5 where the contribution of the flow field is included in the same configuration. The dimensionless parameter controlling the circulation is now the Rayleigh number, which is a measure of the relative importance of gravitational and viscous forces. The effects of the convective overturning adjustment is investigated at different Rayleigh numbers. It is shown that not only is the stratification now always stable, but also that the vigorous vertical mixing reduces the effective Rayleigh number; thereby the flow field is more moderate, the thermocline deepens, and the horizontal surface temperature gradients are weaker. The interior of the fluid is colder compared to cases without convective overturning, and, because the amount of heat in the system is assumed to be fixed, the surface temperature is warmer.

The fluid is not only forced by a mean heat flux, or a seasonally varying one, but its behavior under permanent winter and summer conditions is also investigated. A steady state for the experiments where the net heat flux does not vanish is defined as that state where the flow field and temperature structure are not changing with time except for an almost uniform temperature decrease or increase everywhere. It is found that when winter conditions prevail the circulation is very strong, while it is rather weak for continuous summer forcing. In contrast to those results, if a yearly cycle is imposed, the circulation tends to reach a minimum in the winter time and a maximum in the summer. This suggests that, depending on the Rayleigh number, there is a phase leg of several months between the response of the ocean and the imposed forcing.

Differences between the two averaging procedures mentioned before are also observed when the flow field is present, especially for large Rayleigh numbers. The circulation is found to be weaker and the sea surface temperature colder in the mean of the seasonal realizations compared to the steady state derived by the mean forcing.

As an extension to the numerical results, an analytic model is presented in chapter 4 for a similar annular configuration. The assumed dynamics is a bit different, with a mixed layer on top of a potential vorticity conserving interior. It is demonstrated that the addition of the thermal wind balance to the conservation of potential vorticity in the axially symmetric problem leads to the result that typical fluid trajectories in the interior are straight lines pointing downward going north to south. The passage of information in the system is surprisingly in the

opposite sense to the clockwise direction of the flow.

A model for water mass formation by buoyancy loss in the absence of a flow field is introduced in chapter 3. The idea behind it is to use the turbulent mixing parameterization to generate chimney-like structures in open water, followed by along-isopycnal advection and diffusion. This model can be applied to many observations of mode water. In particular, in this work it is related to the chimneys observed by the MEDOC Group (1970), and the Levantine Intermediate Water in the Eastern Mediterranean Basin. An analytic prediction of the depth of the water mass is derived and depends on the forcing and initial stratification. It suggests that the depth of shallow mode water like the 18°C water or the Levantine Intermediate Water would not be very sensitive to reasonable changes in atmospheric forcing. Similar conclusions were also reached by Warren (1972) by assuming that the temperature in the thermocline decreases linearly with depth, and by approximating the energy balance in a water column by a Newtonian cooling law.

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## THE ENTRAINMENT AND HOMOGENIZATION OF TRACERS WITHIN THE CYCLONIC GULF STREAM RECIRCULATION GYRE

Robert S. Pickart

The various distributions of tracer associated with the Northern Recirculation Gyre of the Gulf Stream (NRG) are studied to try to obtain information about the flow. An advective-diffusive numerical model is implemented to aid in the investigation. The model is composed of a gyre adjacent to a boundary current in which a source of tracer is specified at the upstream edge of the current. This set up attempts to simulate the lateral transfer of properties from the Deep Western Boundary Current (DWBC) to the NRG in the region where the two flows are in close contact west of the Grand Banks.

The results of the model are analyzed in some detail. Tracer is entrained into the gyre as a plume which extends from the boundary current and spirals across streamlines toward the gyre center. The maintenance of the spiral during spin-up and its relationship to the occurrence of homogenization at steady state is examined. An asymmetry in the spiral exists due to the ellipticity of the gyre, which also effects homogenization.

The anomalous properties that are fluxed into the NRG include salt, oxygen, and Freon. These particular tracers are independent from each other, the former two because they are characterized by different vertical profiles in the deep layer. This results in a decay of oxygen but not salt, due to the presence of vertical mixing as discussed by Hogg et al. (1986, Deep-Sea Research, 33, 1139-1165). Their analysis is expanded upon here. The effect of vertical mixing on the gyre/boundary current system is examined within the context of the numerical model. Results are applied to recently collected water sample data from the region which leads to an estimate of the lateral and vertical eddy diffusion coefficients and an estimate of the amount of oxygen in the NRG that has diffused from the DWBC.

The accumulation of Freon within the NRG is considered in addition to salt and oxygen. Appreciable levels of Freon have been present in the ocean only since 1950, and the atmospheric source functions have been increasing steadily since then. A simple overflow model is presented of the manner in which Freon may be stirred in the Norwegian-Greenland basin prior to overflowing and entering the DWBC. Once in the boundary current the concentrations are diluted by way of mixing with surrounding water. Two different schemes are considered in which the immediate surrounding water accumulates a substantial amount of Freon as time progresses. These models suggest that the Freon-11:Freon-12 ratio may not be a conserved quantity for the water in the core of the DWBC. It is found that the level of Freon in the NRG is barely above the existing background level.

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## LASER DIFFRACTION PARTICLE SIZING: SAMPLING AND INVERSION

James B. Riley

The inverse problem of obtaining particle size distributions from observations of the angular distribution of near forward scattered light is reexamined. Asymptotic analysis of the forward problem reveals the information content of the observations, and the sources of nonuniqueness and instability in inverting them. A sampling criterion, such that the observations uniquely specify the size distribution is derived, in terms of the

largest particle size, and an angle above which the intensity is indistinguishable from an asymptote. The instability of inverting unevenly spaced data is compared to that of super-resolving Fourier spectra. Resolution is shown to be inversely proportional to the angular range of observations.

The problem is rephrased so that the size weighted number density is sought from the intensity weighted by the scattering angle cubed. Algorithms which impose positivity and bounds on particle size improve the stability of inversions. The forward problem can be represented by an over-determined matrix equation by choosing a large integration increment in size dependent on the frequency content of the angular intensity, further improving stability.

Experimental data obtained using a linear CCD array illustrates the theory, with standard polystyrene spheres as scatterers. The scattering from single and tri-modal distributions is successfully inverted.

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## THE EFFECT OF A SHALLOW LOW VICOSITY ZONE ON MANTLE FLOW AND ITS EXPRESSION AT THE SURFACE OF THE EARTH

Elizabeth M. Robinson

Many features of the oceanic plates cannot be explained by conductive cooling with age. A number of these anomalies require additional convective thermal sources at depths below the plate: mid-plate swells, the evolution of fracture zones, the mean depth and heat flow relationships with age and the observation of small scale (150-250 km) geoid and topography anomalies in the Central Pacific and Indian oceans. Convective models are presented of the formation and evolution of these features. In particular, the effect of a shallow low viscosity layer in the uppermost mantle on mantle flow and its geoid, topography, gravity and heat flow expression is explored. A simple numerical model is employed of convection in a fluid which has a low viscosity layer lying between a rigid bed and a constant viscosity region. Finite element calculations have been used to determine the effects of (1) the viscosity contrast between the two fluid layers, (2) the thickness of the low viscosity zone, (3) the thickness of the conducting lid, and (4) the Rayleigh number of the fluid based on the viscosity of the lower layer.

A model simple for mid-plate swells is that they are the surface expression of a convection cell driven by a heat flux from below. The low viscosity zone causes the top boundary layer of the convection cell to thin and, at high viscosity contrasts and Rayleigh numbers, it can cause the boundary layer to go unstable. The low viscosity zone also mitigates the transmission of normal stress to the conducting lid so that the topography and geoid anomalies decrease. The geoid anomaly decreases faster than the topography anomaly, however, so that the depth of compensation can appear to be well within the conducting lid. Because the boundary layer is thinned, the elastic plate thickness also decreases and, since the low viscosity allows the fluid to flow faster in the top layer, the uplift time decreases as well. We have compared the results of this modeling to data at the Hawaii, Bermuda, Cape Verde and Marquesas swells, and have found that it can reproduce their observed anomalies. The viscosity contrasts that are required range from 0.2-0.01, which are in agreement with other estimates of shallow viscosity variation in the upper mantle. Also, the estimated viscosity contrast decreases as the age of the swell increases. This trend is consistent with theoretical estimates of the variation of such a low viscosity zone with age.

Fracture zones juxtapose segments of the oceanic plates of different ages and thermal structures. The flow induced by the horizontal temperature gradient at the fracture zone initially downwells immediately adjacent to the fracture zone on the older side, generating cells on either side of the plume. The time scale and characteristic wavelength of this flow depends initially on the viscosity near the largest temperature gradient in the fluid which, in our model, is the viscosity of the low viscosity layer. They therefore depend on both the Rayleigh number and the viscosity contrast between the layers. Eventually the flow extends throughout the box, and the time scales and the characteristic wavelengths of the flow depend on the thickness and viscosity of both layers. When the Rayleigh number based on the viscosity of the top layer, and the depth of both fluid layers, is less tha $10^6$, the geoid anomalies of these flows are dominated by the convective signal. When this Rayleigh number exceeds $10^6$, the geoid anomalies retain a step across the fracture zone out to large ages. We have compared our results to geoid anomalies over Udintsev fracture zone, and have found that the predicted geoid anomalies, with high effective Rayleigh numbers, agree at longer wavelengths with the observed anomalies and can produce the observed

geoid slope-age behaviour. We have also compared the calculated topographic steps to those predicted by the average depth-age relationships observed in the oceans. We have found that only with a low viscosity zone will the flow due to fracture zones not disturb the average depth versus age relationships.

We have also applied the model to a numerical study of the effect of a low viscosity zone in the uppermost mantle on the onset and surface expression of convective instabilities in the cooling oceanic plates. We find that the onset and magnitude of the geoid, topography and heat flow anomalies produced by these instabilities are very sensitive to the viscosity contrast and the Rayleigh number, and that the thickness of the low viscosity zone is constrained by the wavelength of observables. If the Rayleigh number of the low viscosity zone exceeds a critical value then the convection will be confined to the low viscosity zone for a period which depends on the viscosity contrast and the Rayleigh number. The small scale convection will eventually decay into longer wavelength convection which extends throughout the upper mantle, so that the small scale convective signal will eventually be succeeded by a longer wavelength signal. We compare our model to the small scale geoid and topography anomalies observed in the Southeast Pacific. The magnitude (0.50-0.80 m in geoid and 250 m in topography), early onset time (5-10 m.y.) and lifetime (over 40 m.y.) of these anomalies suggest a large viscosity contrast of greater than two orders of magnitude. The trend to longer wavelengths also suggests a high Rayleigh number of near or over $10^6$ and their original 150-250 km wavelength indicates a low viscosity zone of 75-125 km thickness. We have found that the presence of such small scale convection does not disturb the slope of the depth-age curve but elevates it by up to 250 m, and it is not until the onset of long wavelength convecting that the depth-age curves radically depart from a cooling halfspace model. In the Pacific, the depth-age curve is slightly elevated in the region where small scale convection is observed and it does not depart from a halfspace cooling model until an age of 70 m.y. Models that produce the small scale anomalies predict a departure time between 55 and 65 m.y. These calculations also predict an asymptotic heat flow on old ocean floor which is higher than the plate model and between 50 and 55 $mW/m^2$. This value agrees with measurements of heat flow on old seafloor in the Atlantic.

In conclusion, we prefer an approximate model for the viscosity structure of the upper mantle which initially has a 125 km thick low viscosity zone that represents a viscosity contrast of two orders of magnitude. The viscosity contrast decreases as the plate ages to one order of magnitude or less by 130 m.y., and the low viscosity zone may also thicken with age. Finally, the Rayleigh number of the upper mantle is at least $10^5$ and may be as large as $10^7$. With this model, the evolution of the surface plates would initially involve small scale convection which is driven by shear coupling to instabilities down stream and to small scale convection associated with fracture zones. This convective flow would begin at close to 5 m.y. and remain confined to the low viscosity zone until nearly 40 m.y. As this convective flow cools in the upper mantle beneath the low viscosity zone, longer wavelength convection begins throughout the upper (or whole) mantle, and the heat transport from the longer wavelength convection flattens the depth-age curve and may form swells.

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## TIDAL BAND CURRENT VARIABILITY OVER THE NORTHERN CALIFORNIA CONTINENTAL SHELF

Leslie Karen Rosenfeld

Currents of diurnal and semidiurnal frequency measured over the continental shelf off northern California during the Coastal Ocean Dynamics Experiment (CODE) are examined. The diurnal currents are seasonally dependent, with strong surface intensification during the summer. These near-surface diurnal currents are a result of forcing by the local diurnal wind stress. The amplitude of the wind-driven diurnal currents greatly exceeds that of the diurnal tidal currents.

The barotropic semidiurnal tidal currents are estimated by vertical integration of the measured currents over depth. The resulting depth-averaged currents show a large degree of variation over short alongshore length scales, which cannot be explained by existing models used to predict tidal velocities from sea level measurements. Perturbation analysis of a Kelvin wave propagating along a coast with bumps of alongshore scale much less than the Rossby radius of deformation can account for some of the spatial variability observed in the current field.

Depth-dependent semidiurnal tidal currents which vary in strength according to the degree of stratification over the shelf and upper slope were observed during the 1982 upwelling season. The vertical and horizontal structure of these currents and the associated temperature fluctuations

are consistent with first mode internal waves propagating with a shoreward component over a gently sloping bottom.

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## THE TECTONICS AND THREE-DIMENSIONAL STRUCTURE OF SPREADING CENTERS: MICROEARTHQUAKE STUDIES AND TOMOGRAPHIC INVERSIONS

Douglas Ray Toomey

Two-thirds of the Earth's surface has been formed along a global system of spreading centers that are presently manifested in several different structural forms, including the classic rift valley of the Mid-Atlantic Ridge, the more morphologically subdued East Pacific Rise, and the pronounced en echelon structure of the Reykjanes Peninsula within southwestern Iceland. In this thesis, each of these different spreading centers is investigated with microearthquake studies or tomographic inversion of travel times. Results of these studies are used to constrain the spatial variability of physical properties and processes beneath the axis of spreading and, together with other observations, the temporal characteristics of crustal accretion and rifting.

In Chapter 2 the theoretical basis of seismic body-wave travel-time tomography and techniques for the simultaneous inversion for hypocentral parameters and velocity structure are reviewed. A functional analysis approach assures that the theoretical results are independent of model parameterization. An important aspect of this review is the demonstration that travel time anomalies due to path and source effects are nearly independent. The discussion of the simultaneous inverse technique examines theoretically the dependence of tomographic images on the parameterization of the velocity model. In particular, the effects of parameterization on model resolution are examined, and it is shown that an optimum set of parameters averages velocity over localized volumes. Chapter 2 ends with the presentation of the results of tomographic inversions of synthetic data generated for a model of the axial magma chamber postulated to exist beneath the East Pacific Rise. These inversions demonstrate the power of the tomographic method for imaging three-dimensional structure on a scale appropriate to heterogeneity along a spreading ridge axis.

Chapter 3 is the first of two chapters that present the results of a microearthquake experiment carried out within the median valley of the Mid-Atlantic Ridge near 23°N during a three week period in early 1982. In this chapter, the experiment site, the seismic network, the relocation of instruments by acoustic ranging, the hypocenter location method, and the treatment of arrival time data are described. Moreover, hypocentral parameters of the 26 largest microearthquakes are reported; 18 of these events have epicenters and focal depths which are resolvable to within $\pm$ 1 km formal error at the 95 percent confidence level. Microearthquakes occur beneath the inner floor of the median valley and have focal depths generally between 5 and 8 km beneath the seafloor. Composite fault plane solutions for two spatially related groups of microearthquakes beneath the inner floor indicate normal faulting along fault planes that dip at angles of 30° or more. Microearthquakes also occur beneath the steep eastern inner rift mountains. The rift mountain earthquakes have nominal focal depths of 5-7 km and epicenters as distant as 10-15 km from the center of the median valley. The depth distribution and source mechanisms of these microearthquakes are interpreted to indicate that this segment of ridge axis is undergoing brittle failure under extension to a depth of at least 7-8 km.

In Chapter 4, the population of earthquakes considered in Chapter 3 is doubled and is used to define seismicity trends, to improve source mechanisms, and to estimate seismic moment and source dimensions of selected events. From a total of 53 microearthquakes, 23 are located beneath the inner floor and the epicenters of 20 of these occur within approximately 1 km of a line which strikes N25°E; this seismicity trend is over 17 km in length. For 12 events located along the seismicity trend, the composite fault plane solutions clearly indicate normal faulting along planes that dip near 45°. The seismic moments of inner floor microearthquakes are in the range $10^{17}$-$10^{20}$ dyn cm, and a B value of $0.8\pm0.2$ is determined for events with moments greater than $10^{18}$dyn cm. Epicenters of rift mountain earthquakes do not appear to define linear trends; however, over a 24 hour period a high concentration of activity within a small area was observed. The seismic moments of events beneath the inner rift mountains vary between $10^{18}$ and $10^{20}$ dyn cm and define a B value of $0.5\pm0.1$.

Also in Chapter 4, a tomographic inversion of travel times from earthquakes and local shots indicates a region of relatively lower velocities at 1-5 km depth beneath the central portion of the median valley inner floor, presumably the site of most recent crustal accretion. Results of microearthquake analysis and tomographic

inversion are synthesized with local bathymetry and the record of larger earthquakes in the region to suggest that this section of the median valley has been undergoing continued horizontal extension and modest block rotation without crustal-level magma injection for at least the last $10^4$ yr.

In Chapter 5, the simultaneous inverse technique is applied to a microearthquake data set collected at the Hengill central volcano and geothermal complex in southwestern Iceland. Arrival time data from 153 well-located microearthquakes and 2 shots, as recorded by 20 vertical component seismometers, are used to image velocity heterogeneity within a 14 x 15 x 6 $km^3$ volume that underlies the high-temperature Hengill geothermal field. The dense distribution of sources and receivers within the volume to be imaged permits structure to be resolved to within $\pm 1$ and $\pm 2$ km in the vertical and horizontal directions, respectively. The final model of structural heterogeneity is characterized by distinct bodies of anomously high velocities: two of these bodies are continuous from the surface to a depth of about 3 km, and each is associated with a site of past volcanic eruption; the third body of high velocity lies beneath the center of the active geothermal field at depths of 3-4 km.

The results of this thesis demonstrate that microearthquake surveying and seismic tomography are powerful tools for investigating the spatial variability of the dynamic processes that accompany the generation and early evolution of oceanic lithosphere.

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## MIXING AND GENERAL CIRCULATION DYNAMICS: THEORY AND OBSERVATIONS

Eli Tziperman

This thesis studies the role of cross-isopycnal mixing in general circulation dynamics, from both the theoretical and observational points of view.

The first two chapters discuss some theoretical aspects of cross-isopycnal mixing in the oceans. In chapter one, an integral constraint relating the interior stratification and air-sea heat fluxes is derived, based on the condition that the total mass of water of given density is constant in a steady state ocean. Two simple models are then used to examine the way the numerically small mixing, together with air-sea fluxes, determines the average vertical density stratification of the oceans, and the deep buoyancy driven circulation.

In chapter two, a more complete model of a deep flow driven by cross isopycnal diffusion is presented, motivated by the Mediterranean outflow into the North Atlantic. Mixing in this model is responsible for the determination of the detailed structure of the flow and density field, while in the models of the first chapter it was allowed to determine only the average vertical density stratification.

In chapter three, a hydrographic data set from the Mediterranean sea is analyzed by inverse methods. The purpose is to examine the importance of mixing when trying to explain tracer distributions in the ocean. The time-mean circulation and the appropriate mixing coefficients are calculated from the hydrographic data.

We conclude that the numerically small cross isopycnal mixing processes are crucial to the dynamics, yet difficult to parameterize and measure using available hydrographic data.

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